The Navigation Economic Technologies Program

November 1, 2004

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A Discrete Event Simulation Model of a Congested Segment of the Upper Mississippi River Inland Navigation System

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IWR Report 04-NETS-R-01

Navigation Economic Technologies

The purpose of the Navigation Economic Technologies (NETS) research program is to develop a standardized and defensible suite of economic tools for navigation improvement evaluation. NETS addresses specific navigation economic evaluation and modeling issues that have been raised inside and outside the Corps and is responsive to our commitment to develop and use peer-reviewed tools, techniques and procedures as expressed in the Civil Works strategic plan. The new tools and techniques developed by the NETS research program are to be based on 1) reviews of economic theory, 2) current practices across the Corps (and elsewhere), 3) data needs and availability, and 4) peer recommendations.

The NETS research program has two focus points: expansion of the body of knowledge about the economics underlying uses of the waterways; and creation of a toolbox of practical planning models, methods and techniques that can be applied to a variety of situations.

Expanding the Body of Knowledge

NETS will strive to expand the available body of knowledge about core concepts underlying navigation economic models through the development of scientific papers and reports. For example, NETS will explore how the economic benefits of building new navigation projects are affected by market conditions and/or changes in shipper behaviors, particularly decisions to switch to non-water modes of transportation. The results of such studies will help Corps planners determine whether their economic models are based on realistic premises.

Creating a Planning Toolbox

The NETS research program will develop a series of practical tools and techniques that can be used by Corps navigation planners. The centerpiece of these efforts will be a suite of simulation models. The suite will include models for forecasting international and domestic traffic flows and how they may change with project improvements. It will also include a regional traffic routing model that identifies the annual quantities from each origin and the routes used to satisfy the forecasted demand at each destination. Finally, the suite will include a microscopic event model that generates and routes individual shipments through a system from commodity origin to destination to evaluate non-structural and reliability based measures.

This suite of economic models will enable Corps planners across the country to develop consistent, accurate, useful and comparable analyses regarding the likely impact of changes to navigation infrastructure or systems.

NETS research has been accomplished by a team of academicians, contractors and Corps employees in consultation with other Federal agencies, including the US DOT and USDA; and the Corps Planning Centers of Expertise for Inland and Deep Draft Navigation.

For further information on the NETS research program, please contact:

Mr. Keith Hofseth
NETS Technical Director
703-428-6468

Dr. John Singley
NETS Program Manager
703-428-6219

U.S. Department of the Army
Corps of Engineers
Institute for Water Resources
Casey Building, 7701 Telegraph Road
Alexandria, VA 22315-3868

The NETS program was overseen by Mr. Robert Pietrowsky, Director of the Institute for Water Resources.

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A DISCRETE EVENT SIMULATION MODEL OF A CONGESTED SEGMENT OF THE UPPER MISSISSIPPI RIVER INLAND NAVIGATION SYSTEM

Prepared by:

Donald C. Sweeney
The Center for Transportation Studies
University of Missouri

For the:

Institute for Water Resources
U.S. Army Corps of Engineers
Alexandria, Virginia

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by

Donald C. Sweeney II

Visiting Scholar

The Center for Transportation Studies

University of Missouri, St. Louis

Prepared for the U.S. Army Corps of Engineers

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Abstract

A Discrete Event Simulation Model of a Congested Segment of the Upper Mississippi River Inland Navigation System

by

Donald C. Sweeney II

A discrete event based simulation model is presented and evaluated for use in investigating changes to the operational characteristics of an important segment of the Upper Mississippi River inland navigation system. The simulation model extends earlier inland navigation simulation models of systems of locks by explicitly incorporating seasonal and interdependent traffic demands for specific origin and destination trips into the model.

An analysis of U.S. Army Corps of Engineers OMNI data compiled from the Upper Mississippi River during the period from 2000 through 2003 is presented which indicates that the most heavily utilized locks of the Upper Mississippi River experience periodic traffic congestion, are subject to seasonal changes in demands for service, and operate as a connected system of locks in that they share a large amount of common interrelated commercial tow traffic. The simulation model is calibrated to this historic data and shown to reasonably represent the overall operation of the system including the periodic seasonality of the demand for lock use evident in the Corps OMNI data.

The simulation model is employed to identify and examine the potential impacts of the implementation of a SPF, shortest processing time first, lock queue tow dispatch policy for a relatively congested segment of the Upper Mississippi River navigation system. The implementation of this queue tow dispatch policy has a relatively small expected impact on the operation of the simulated UMR system when compared with the operation of the system under the existing first-in, first out lock queue tow dispatch policy. The SPF dispatch policy increases the expected efficiency of the simulated system by approximately 0.5 percent by reducing expected lock transit times in the simulated system by approximately nine percent. The very small increase in expected system efficiency is a consequence of the seasonality of demand for the use of the system and the very small proportion of time that tows engage in activities at these locks which together mute the response of simulated tows to the SPF policy. If real tows operating on the UMR respond similarly, there will be on average only a small response in the system to the reduced lock service delays and increased lock efficiencies created by the implementation of a SPF lock queue dispatch policy.

Other changes to the operating characteristics of the UMR may be readily examined in the framework adopted by the model by incorporating the changed operating characteristics of the system in the simulation model and then evaluating the resulting impacts to system performance. Finally, useful extensions of the UMR simulation model are discussed and the data requirements needed to implement these model extensions are identified

1. INTRODUCTION

The purpose of this research is to create and evaluate a discrete event based simulation tool for use in investigating changes to the operational characteristics of an important segment of the inland navigation transportation system. The lower five 600 feet long locks of the Upper Mississippi River (UMR) navigation system provide a useful setting for testing such a simulation model as these five locks experience periodic traffic congestion, are subject to seasonal changes in demands for service, operate as a system in that they share a large amount of common interrelated commercial tow traffic, and have been the subject of significant controversy regarding their possible replacement with costly larger sized, lock chambers.

The simulation model developed for the UMR navigation system differs from prior waterways simulation models in two important dimensions. First, the UMR navigation system model explicitly embodies the fact that the demand for use of the UMR is highly seasonal in nature and that the UMR system never achieves or approximates a steady state level of system performance. The lack of steady state performance characteristics is the direct result of annually repeating and readily predictable periods of relatively high and low demands for use of the system. Therefore, the steady state queuing system models used to approximate the operating conditions of the UMR used in existing Corps of Engineers system economic models are not appropriate and may distort the economic evaluation of potential changes to the operating conditions or infrastructure of the system. Second, the UMR navigation system simulation model explicitly incorporates the fact that the production of individual system movements can not be independent of each other as the waterway transportation equipment needed to complete each movement must first be delivered to the origin of the movement from some other waterway location. Hence, the supply of equipment required to complete individual water movements is related to other system movements and the resulting performance of individual locks within the system will be linked by the common tow traffic of the interrelated trips. Therefore, system performance characteristics such as queue sizes and waits for service at system locks will be related and modeling these locks as a sequence of independent servers is not appropriate. Consequently, navigation system economic models that incorporate the assumption that locks operate as independent servers may distort the evaluation of potential changes to the operating conditions or infrastructure of the navigation system.

The interdependency of lock operations created by the service of common tow traffic and the existence of periods of high and low levels of demand for use of the system provide currently untapped sources of efficiency improvements for the implementation of alternative traffic management policies in the operation of the UMR system. Specifically, system efficiencies can be created by scheduling traffic, re-sequencing vessels for processing at the locks or by providing economic incentives for decreasing system use during high demand periods and increasing system use during low demand periods. Existing system economic models used by the Corps of Engineers cannot properly incorporate or evaluate these potential operational improvements.

2. THE UPPER MISSISSIPPI RIVER NAVIGATION SYSTEM

The Upper Mississippi River is an integral part of a national inland water transportation network. The UMR river navigation system provides an important transportation link both into and out of

America’s Midwest. The UMR navigation system extends approximately 663 linear miles from just north of Minneapolis, MN, southward to the confluence of the Mississippi and Missouri Rivers near St. Louis, MO. Reliable navigation conditions are created in the system by a series of 29 lock and dam facilities which maintain a minimum usable channel depth of nine feet for the entire length of the navigable system. Figure 1 presents a map of the UMR portion of the inland navigation system.

The UMR lock and dam system was originally constructed beginning in the 1930’s under the authority of the 1930 Rivers and Harbors Act. This legislation directed the U.S. Army Corps of Engineers to construct and maintain a navigation channel with a minimum depth of nine feet. The dams were constructed to retain enough river flow to permit sufficient depth for navigation of commercial tows and other vessels. A series of interconnected water stair steps, called pools, are created by the dams to ensure the desired navigation conditions in the system. The lock chambers were constructed to permit the navigation traffic to pass through the dams and thereby navigate to the next pool in the water staircase. Figure 2 presents a schematic view of the UMR pool system.

The original locks were constructed with main chambers 600 feet in length that were designed to accommodate the largest commercial tows of the 1930’s and 1940’s. However, over the ensuing decades, towboats on the UMR have become larger and individual flotillas pushed by tows are composed of more and larger barges. Most fully assembled tows on the river today exceed 600 feet in length and require that a group of barges be decoupled from the fully assembled tow in order for the tow to pass through the locks. These segments of tows are termed cuts. These cuts are subsequently re-coupled after passage of the entire tow through the lock as the fully assembled tow continues transiting the system. With rare exceptions, the largest tows operating in the UMR system require two cuts to pass through a 600 foot long lock. These “double lockages” require a relatively lengthy processing time for these tows to pass through UMR locks and contribute to periodic congestion evident at some locks on the lower portion of the Upper Mississippi River. Selected important physical and operational characteristics of the UMR locks are summarized in Table 1.

Agricultural products are the primary commodities transported in the UMR navigation system and account for a majority of the annual volume of commercial shipping activity. The UMR also serves as a major artery for the transport of other bulk commodities such as chemical products, coal, cement, and petroleum products. Most products shipped on the UMR system are intermediate or raw goods destined primarily for use in the ultimate production of other final consumer goods and products.

Commercial navigation on the Upper Mississippi River plays an important role in the national and regional economy. The historic importance of the UMR as a shipping artery is reflected in the increase in tonnage shipped on the system. Tonnage shipped on the system increased from approximately 27 million tons in 1960 to approximately 84 million tons in 2002. At present, there are more than one hundred terminals on the UMR that ship and receive commodities.

Towboats currently moving on the UMR may exceed 5,000 horsepower, push a typical tow composed of up to 16 barges, and routinely exceed 1,100 feet in length when fully assembled.

The four primary types of barges employed on the UMR to carry commodities are open hopper barges, covered hopper barges, deck barges, and tank barges. Open hopper barges are used for moving many types of bulk solid cargo such as coal, raw mineral products, and aggregates and account for some 45 percent of the carrying capacity of all barges operating on the inland waterways. Covered hopper barges carry mainly grain and fertilizer products and account for some 25 percent of the total tonnage capacity nationwide. Tank barges, used for transporting petroleum and chemical products, and deck barges, used for moving a wide variety of products, make up approximately 22 and eight percent of the national barge fleet, respectively. Covered and open hopper barges can transport over 1,500 tons of products per barge, tank barges can transport over 2,000 tons of products per barge, and deck barges vary substantially in their cargo carrying capacity.

Lockage delays in the UMR navigation system occur primarily as a result of the large volume of tonnage shipped through the system at various times of the year. To a lesser and more variable extent, unusual events such as lock malfunctions, tow pilot errors, and adverse vessel or lock operating conditions also contribute to the delays periodically evidenced at these locks. Built beginning in the 1930's, the lock system was originally designed to readily accommodate tow sizes of up to 600 feet in length. In response to the increased volume of tonnage demand and the economies of larger shipment sizes, tows now routinely push 15 barges with a total length near 1,200 feet. These large tows require lengthy double lockages to pass through the locks and greatly contribute to lockage delays. Also, significant use of the UMR locks by non-commercial vessels, such as privately owned recreation craft, periodically throughout the year contributes to lockage delays in the UMR system.

The five southernmost 600 foot long locks of the UMR navigation system, Locks 20, 21, 22, 24 and 25 (there is no Lock 23) are the most heavily utilized 600 foot long locks and are among the most congested of all locks in the inland navigation system. Table 2, compiled from U.S. Army Corps of Engineers OMNI lock data for calendar years 2000 through 2003, displays by month the mean number of lockages completed and the mean and standard deviation of the time spent by vessels waiting for service at these five locks. Table 2 reveals that a total of 70,180 lockages were completed at these locks during the four year period (an average of 3,509 lockages per lock per year) and that vessels waited an average of 2.4 hours per lockage before beginning processing at a lock. Also clearly evident in Table 2 is the relatively large variability of the distribution of the wait for service time observed throughout the entire four year period.

Of the 70,180 total lockages summarized in Table 2, 58,964 lockages (84% of the total) represent the lockage of commercial tows. These commercial tow lockages were produced by a total of 382 unique tow boats operating at these locks over the four year period with an average of 242 unique tow boats operating at these locks in any given year. These commercial tows waited an average of 2.8 hours per lockage at these five locks. The slightly greater mean wait time of commercial tows compared to the overall mean wait time of 2.4 hours for all vessels reflects the relative priority in the system placed on expeditiously completing non-commercial recreation craft lockages. Corps regulations governing recreational craft lockages state that recreational craft may not be required to wait for more than the completion of three commercial tow lockages. In practice, recreational vessels rarely even wait that long for service. For example, in many cases, recreational vessels are opportunistically locked between successive commercial tow lockages during the lock chamber turnback needed to process the next tow when the commercial tows are moving through the lock in the same direction. Further, multiple recreation vessels may simultaneously utilize the lock chamber in a single lockage operation and are therefore moved out of their arrival sequence in order to fill the chamber with as many waiting recreational vessels traveling in the same direction as possible.

Table 2 further reveals that the monthly distribution of the total number of lockages completed at these five locks is highly seasonal in nature. The demand for lock use annually builds from a very low level in the winter months to a peak level of use in July and August and then gradually declines through the fall months back to a very low level of use by the end of each calendar year. A system is said to be in a steady state when the state of the system is independent of the time of the observation of the system. A characteristic of a steady state system is that its arrival and service rates do not change with time. Clearly, this subsystem of the UMR system never achieves a steady state as the vessel arrival rates change significantly throughout the calendar year. Consequently, this high degree of seasonality evidenced in system usage levels renders steady state models and steady state queuing system approximations as potentially poor indicators of the real operating conditions evidenced at these five locks. A more detailed examination of the operating conditions observed at these locks is presented below in Section 4.

3. CHARACTERISTICS OF THE U.S. ARMY CORPS OF ENGINEERS OMNI DATABASE

The Institute for Water Resources (IWR) of the U.S. Army Corps of Engineers (USACE) provided a Microsoft Access database containing tow traffic data recorded by the Corps of Engineers OMNI database system at all Upper Mississippi River locks for calendar years 2000 through 2003. The database consists of several interrelated tables including: a table containing detailed lock traffic and lock performance data recorded from 2000 through 2003; a table containing detailed information regarding the flotilla of barges making up each commercial tow when it passed through a UMR lock; a table containing detailed information regarding the physical characteristics of the towboats operating on the inland navigation system; and a table containing detailed information regarding the physical lock operations associated with each individual UMR lockage.

The subset of records in the original OMNI database related to the tow traffic through Upper Mississippi River Locks 20, 21, 22, 24 and 25 is extracted for analysis and use in the construction of a model designed to simulate the flow of tow traffic through this subsystem of locks. A detailed description of the individual OMNI databases, the procedure employed to identify and extract the data needed for the simulation model, and the subsequent calculations and analyses required to prepare the extracted data into the format required by the simulation model are presented below.

Traffic Table

The OMNI Traffic Table serves as the primary data table for the analysis of system traffic. This table contains a unique record for each transaction completed at each lock represented in the OMNI database. A transaction is the passage of a flotilla (or a portion of a flotilla) through a system lock. Flotillas are composed of commercial tows with barges, government owned vessels, private recreation vessels, light boats (commercial tows without barges) and commercial passenger vessels. These transactions are termed lock operations and each individual record in the Traffic Table is assigned a unique operations ID by the Corps OMNI system. Many flotillas have multiple operations ID's associated with a single lock passage as the lockage of many commercial tows requires multiple "cuts" (the lockage of a portion of a fully assembled tow that is itself too large to pass through the lock in a single lock operation) to complete the transit of the tow through a lock. In contrast, other transactions in the Traffic Table represent the simultaneous passage of multiple vessels through the lock in a single lock operation when the flotilla is composed of multiple recreation craft or multiple light boats processed in a single lockage. Each database record in the Traffic Table contains numerous fields of information regarding the lock, the flotilla associated with the lock operation, and the detailed timing data associated with the lock operation. The important fields in each Traffic Table record are listed below in Table 3 and the asterisks associated with the fields listed in Table 3 indicate data fields that are used to construct the simulation model input database.

Flotilla Table

This OMNI database table contains detailed information regarding the vessels in the flotillas associated with each lock transaction. Unique flotilla numbers are assigned to each vessel or combination of vessels at each lock transited and associated with both the Flotilla Table and Traffic Table records corresponding to each lockage. Unfortunately, however, the flotilla numbers in the original OMNI Traffic Table supplied by the Corps did not correspond with the flotilla numbers included in the associated Traffic Table. Therefore, the Flotilla Table and the characteristics of the individual flotillas were unavailable for use in the construction of the simulation model. Table 4 displays the important data fields contained in the Flotilla Table.

Vessel Table

This OMNI database table contains detailed information regarding the physical characteristics of towboats and other vessels associated with the records in the Traffic Table. Information regarding vessel ownership, vessel type and the vessel horse power are included in this database table. Table 5 below displays the important data fields contained in the Vessel Table.

Operations Table

This OMNI database table contains information regarding the details of the physical operations associated with individual lock operations. This information includes the direction (up-bound or down-bound) of travel of the flotilla associated with the lock operation. Table 6 below displays the important data fields contained in the Operations Table.

4. ANALYSIS OF THE CORPS OF ENGINEERS OMNI DATABASE

Version 12.0.2 of SPSS for Windows is utilized to manage and analyze the data contained in the Corps of Engineers OMNI database. SPSS offers a suite of powerful and easy-to-use tools to clean, format, manage, and generate statistical and distributional information from a SPSS database created from the original Corps OMNI database.

Creation of the SPSS Database

As described in Section 2 above, the OMNI Traffic Table served as the foundation for creating the SPSS database. All other needed data fields from the other related OMNI database tables were appended to the original OMNI Traffic Table to create the SPSS database. The procedure utilized to create the SPSS database is outlined below.

- The direction of vessel travel field (upbound or downbound) from the OMNI Operations Table is appended to the records in the OMNI Traffic Table.

- An attempt to append the number of loaded barges, empty barges, and vessel stop information in the OMNI Flotilla Table to the OMNI Traffic Table was unsuccessful as the Flotilla identification numbers included in the Flotilla Table did not match the Flotilla identification numbers included in the OMNI Traffic Table. Ultimately, the Corps did provide a corrected OMNI Flotilla Table with corrected flotilla numbers, but the creation of the simulation model preceded the provision of this amended file and the simulation model was constructed without the benefit of this data.

- The vessel type and vessel horse power fields from the OMNI Vessel Table are appended to the records in the OMNI Traffic Table. This final appended OMNI Traffic Table is then imported into a master SPSS data table containing the data needed for this analysis and construction of the simulation model. In this SPSS master table, there are a total of 114,692 records which includes multiple records for individual lockages of tows that required more than a single cut to transit a lock.

- The multiple records associated with each multi-cut commercial tow lockage are combined into a single SPSS data record containing the start of the lockage time for the first cut and the end of the lockage time for the final cut included in the new single lockage record. This procedure produces a single record containing the start of lockage time and the end of lockage for each multi-cut tow. Completing this procedure results in a final SPSS database containing 70,180 unique lockage records for UMR Locks 20 through 25 for calendar years 2000 through 2003.

- The time required to complete each of these individual lockages is then calculated as the total amount of time between the recorded start of the lockage and the recorded end of the lockage. The waiting time for each individual lockage is calculated as the total amount of time between the recorded arrival time of the vessel at the lock and the recorded start of lockage time for that lockage. Distributions of these two variables measured in hours and aggregated over the five locks are illustrated in Figure 3 and Figure 4, respectively.

As evidenced in Figure 3, the distribution of lockage times at these five locks is very clearly bi-modal. This bi-modal distribution of lockage times is the result of two very different underlying lockage distributions that characterize lockages at these five locks; one underlying distribution for commercial tows that are over 600 feet in length which require two separate cuts to complete a single lockage and a second underlying distribution for commercial tows and other vessels that are less than 600 feet long which only require a single cut to complete a lockage.

As evidenced in Figure 4, a significant portion of the vessels transiting these five locks, approximately 31 percent, were processed with little or no wait for service after arriving at a lock. Approximately one half of all vessels waited less than one hour for service. The remaining fifty percent of vessels waited for varying durations before being processed through a lock with the vast majority of these vessels waiting for periods of less than 6 hours before receiving service. Finally, a small but significant proportion, approximately 10 percent, of the vessels arriving at the locks waited more than 6 hours or more before service was provided.

Analysis of the Data

Distributions of Lock Specific Wait and Lockage Times

Inspection of individual lock wait and lockage time distributions indicates that there are differences evident in these distributions between locks, so selected summary statistics of wait and lockage time distributions for each individual lock by direction of movement and vessel type are generated and inspected. The direction of movement of a vessel at a lock is defined relative to the natural flow of the river, either upbound or downbound. Three different vessel types are employed to characterize the vessels transiting each of the five locks. The vessel type “multi-cut tows” represents commercial tows requiring multiple cuts to complete a single lockage, the vessel type “single cut tows” represents commercial tows with barges that require only a single cut to complete a lockage, and the vessel type “Other Vessels” represents all other traffic at a lock. The vessel type “Other Vessels” is composed of recreational vessels, commercial passenger vessels, “light” commercial towboats (commercial towboats without barges), and federal government owned vessels.

Selected summary statistics of the wait for lockage time distributions are presented in Table 7 and selected summary statistics of the lockage time distributions are presented in Table 8. As evidenced in Tables 7 and 8, the distributions of wait and lockage times characterized by lock, vessel type, and direction of travel exhibit significantly different summary statistics. For example, Table 7 reveals that the mean wait times for lockage are significantly greater for all vessel types at Locks 22, 24, and 25 than they are at Locks 20 and 21. Also, Table 7 reveals that the wait for lockage times of “other” vessels are significantly less than the wait for lockage times exhibited for multi-cut and single cut commercial tows. This difference reflects the greater priority assigned to completing recreation vessel lockages relative to the priority assigned to completing commercial tow lockages in the queue dispatch policies currently implemented for the locks in the UMR. Further, Table 8 reveals that there are significant differences between mean lockage times characterized by vessel type at all of the locks both individually and collectively. Consequently, these more finely partitioned conditional distributions of lockage times are utilized to represent the processing of traffic at the different locks in the simulation model.

Distributions of Transit Times between Locks for Commercial Tows

The implied transit time for vessels moving through the pools connecting the locks may be estimated as the amount of time observed between the recorded arrival time at a lock for a vessel and the recorded end of lockage time at the previous lock transited by that vessel. These implied travel times often include many different activities undertaken by vessels between consecutive appearances at UMR locks as not all commercial tows move non-stop from one lock in the system to another lock in the system. These implied pool transit times are estimated for all multi-cut and single cut tow lockage sequences observed in the database. Estimates of implied transit times are not computed for other vessel transits because the majority of other vessel lockages in the system involve the lockage of recreation craft where a unique identification of the vessel involved in the lockage is not contained in the data. Also excluded from these implied transit time estimates are tow lockage sequences identified in the data with an implied negative travel time from one lock to another and tow lockage sequences that are physically impossible. For example, an observed tow transit consisting of a downbound lockage at UMR Lock 22 followed sequentially by an upbound lockage at UMR Lock 24 is excluded from the travel time estimates as such a tow movement is physically impossible. Inspection of the data reveals that the anomalous tow lock transitions and negative tow travel times are most likely created by miscoded vessel identification numbers, miscoded lockage and arrival dates, and the fact that not all tow identification numbers are recorded for all light boats moving through a lock together in multiple vessel lockages.

The distributions of implied tow transit times are generated for each possible combination of origin lock, destination lock, lockage type (single cut or multi-cut tow at the destination lock), direction of travel at the origin lock, and direction of travel at the destination lock. The summary statistics of these distributions are displayed in Table 9 for multi-cut tows and in Table 10 for single cut tows.

Of note in Tables 9 and 10 are the very long mean transit times for upbound tows exiting Lock 20 and downbound tows exiting Lock 25. These very lengthy transit times are the result of the fact that these tows are sequentially observed in the extracted database of lockages only when they return to the very same lock, but moving in the opposite direction. Consequently, all of the many interim activities that these tows engage in north of Lock 20 or south of Lock 25 occur between these sequential database observations thereby creating lengthy transit times with large variability.

As evidenced in Tables 9 and 10 the distributions of implied tow transit times are clearly dependent on the origin lock, the destination lock, the tow type, the direction of travel at the origin lock, and the direction of travel at the destination lock. For example, the mean implied transit time from Lock 21 to Lock 20 (upbound travel of the entire length of Pool 21) for a multi-cut tow is 3.95 hours with a standard deviation of 4.04 hours. In contrast, the mean implied travel time for the same upbound transit of the entire length of Pool 21 for a single cut tow is 5.68 hours with a standard deviation of 29.58 hours. For multi-cut tows completing a downbound transit of the entire length of Pool 21, the mean transit time from Lock 20 to Lock 21 is 2.69 hours with a standard deviation of 4.01 hours. For single cut tows completing the same transit the mean transition time is 8.85 hours with a standard deviation of 81.40 hours. Generally, the mean transit times for upbound tow travel from one lock to another lock are greater than the mean transit times for downbound tow travel for the same lock pair. The mean transit times for tows that change their direction of travel in a pool between successive lockages are relatively large with relatively large variation because of the intra-pool activities undertaken by these tows (delivering barges, picking up barges, or fleeting barges) when reversing their direction of travel. The summary statistics further demonstrate that single cut tows have substantially greater variability in their transit time distributions and circulate through the system more slowly than do multi-cut tows.

Tables 9 and 10 also highlight the significantly different manner in which multi-cut tows and single cut tows utilize the system composed of these five locks. Nearly all multi-cut tows transit the entire five lock system before exiting the system either as an upbound lockage at Lock 20 or a downbound lockage at Lock 25 and then ultimately return at some later date to transit the entire five lock system again in the opposite direction. Single cut tows, however, display a significant non-zero probability of changing their direction of travel in some pool between Lock 20 and Lock 25 and, consequently, do not tend to navigate through the entire five lock system in a single direction or single transit. For example, Table 10 indicates that 392 of the 976 single cut downbound tow lockages observed at Lock 21 returned to Lock 21 as an upbound tow for their next observed lockage. This represents approximately 40 percent of the total downbound single cut tow traffic through Lock 21 which contrasts dramatically with the 1.5 percent (69 of 4,507) of multi-cut tows that Table 9 indicates behave in a similar manner.

Correlation Coefficient for Wait Times at Sequential Locks

The Bivariate Pearson coefficient of correlation computed for the successive wait for lockage times at locks transited sequentially by individual tows is a useful summary statistic for investigating the relationship between the concurrent operating conditions of the various locks in the system caused by the processing of common tow traffic. For example, if tows that wait a relatively long period for service at a given lock in the system also tend to wait a relatively long period for service at the next lock the tow transits during the same voyage, then there is evidence of a direct relationship between the concurrent operating conditions of the individual locks. If there is evidence that the concurrent operating conditions are related to each other, then there is evidence that the system of locks does not behave as a series of independent lock servers with traffic arrival patterns, service times, and wait times determined independently of the operating conditions of the other locks in the system.

The subset of lockages that represent sequential commercial tow movements from one system lock to an adjacent system lock in the extracted database contains 43,563 cases. The Bivariate Pearson correlation coefficient for the wait time encountered by these vessels at sequential locks is equal to 0.254 which is significantly different from zero at the 0.0001 level. This significant, small and positive correlation of wait times encountered by tows at successive locks when moving through the system implies that when a tow encounters a long wait time at a system lock, it also tends to encounter long wait times at adjacent system locks. Therefore, the concurrent operating conditions evident at the system locks are directly related when processing common tow traffic. Consequently, the concurrent operating conditions at these five locks exhibit interdependence and the system of locks does not behave as a system of independent lock servers. In other words, the operating conditions at individual locks as characterized by inter-arrival distributions, service time distributions, and wait times distributions are co-determined as a result of processing common tow traffic moving through the system.

Evidence of Seasonality in the UMR System

As the UMR is a seasonal navigation system with relatively high usage rates in the summer and relatively low usage rates in the winter, the distributions of selected operating characteristics are partitioned by the calendar month of their occurrence to examine how the operating characteristics of the system change though time. Figure 5, below, presents the number of vessel arrivals by month at each lock during the period from 2000 through 2003. Note that each of the locks exhibits a similar pattern of regular seasonal variability in monthly vessel arrivals. There is very low demand for lockage services in January and February at all five of the locks. Then, beginning in March, the number of vessel arrivals dramatically increases over the very low arrival rates evident in the winter months. The number of vessel arrivals increases again at a somewhat decreased rate though through May and June until the number of arrivals peaks during

July and August. Beginning in September, there is a noticeable decrease in vessel arrivals from the summer peak levels to a relatively stable lower rate of arrivals that continues through the late fall months. Finally, in December the arrival rates rapidly decrease to return to the very low levels evidenced in January and February. This seasonal pattern of vessel arrivals is evident in each of the four years of data separately as well as in the aggregated data displayed in Figure 5.

Figure 6 displays the aggregated wait for lockage times characterized by the month of lockage summed over all vessels using each of the locks during the period from 2000 through 2003. As might be anticipated from the seasonal pattern of vessel arrivals observed at the locks, the aggregated wait for lockage times also exhibit a high degree of regular seasonal variability. The aggregated wait for lockage times increase rapidly throughout the spring months, reach their peaks in the summer months, and then gradually decrease throughout the fall months to return to relatively low levels in the winter months.   Figure 6 also reveals that Lock 22, Lock 24, and Lock 25 are generally more congested when measured by total vessel wait for lockage time than are Lock 20 and Lock 21.

Figure 7 displays the mean transit times for tows transiting the entire lengths of Pool 21, Pool 22, Pool 23, and Pool 24 by month during the period 2000 through 2003. With the exception of the winter months there does not appear to be significant seasonality evident in the mean transit times of tows moving through the pools between the locks. The northernmost of these pools, Pool 21 and Pool 22, do show some inconclusive evidence of longer mean transit times during the winter months, however, these longer mean transit times are generated by a very small number of observed tow transits. For example, there was a single pool transit observed in Pool 21 and a total of 19 pool transits observed in Pool 22 during the four January months contained in these four years of observations.

Figure 8 displays the mean lockage times for vessels by month for each of the locks during the period from 2000 through 2003. Again, there is some evidence of seasonality present in the monthly distributions of mean vessel lockage times observed at each of the locks. The mean lockage times are lower in the June through September period at each of the locks than the mean lockage times observed during the remainder of the year. This is primarily the result of the greater proportion of local recreation vessels completing lockages at the locks during the high recreation use months of the summer. Recreation vessels typically produce very quick lockages. The distributions of lockage times observed for commercial tows do not exhibit any regular seasonality during the same time period.

There is clear evidence of regular seasonality exhibited in the annual operation of this segment of the UMR. The seasonality through the year appears to be driven primarily by differing levels of system use by vessels rather than by significant differences in the operating characteristics (travel times and lockage times) of the vessels or the locks. To highlight the importance of the differing levels of system use in contributing to the seasonality evidenced in the system, Figure 9 displays by date the total number of commercial tows that have produced their first system lockage of the year and that have not yet produced their final system lockage for that calendar year. Figure 9 clearly shows the seasonality of commercial tow demand for use of the system.

Figure 10 presents details regarding the date of the first annual lockage completed by individual tows at these five UMR locks.   As evidenced in the chart, a relatively small number of tows operate in the system during the winter months. As the weather and operating conditions improve in the early spring there is a significant and rapid increase in the number of tows that complete their first annual lockage in the system. As the year progresses, new tows continue to enter the system to complete their initial annual lockage in the system, but at a declining rate. The decline in the number of new arrivals to the system continues throughout the summer months such that by the late fall only a handful of new tows that have not already appeared in the system enter the system for their first annual lockage.

Figure 11 presents details regarding the date of the final annual lockage completed by individual tows at the UMR locks. As evidenced in Figure 11, a relatively small number of tows complete their final system lockage early in the year. As the year progresses, a greater but still relatively small number of tows complete their final system lockage during the late spring and summer months, however, most tows continue to use the UMR system through the entire calendar year with the vast majority of individual tows producing their last annual lockage during the final two months of the year.

To summarize, there is clear evidence of regular seasonality exhibited in the annual operation of this segment of the UMR. The seasonality appears to be driven primarily by regularly differing levels of demand for system use evidenced by both commercial and non-commercial vessels throughout the calendar year rather than by significant differences in the operating characteristics (travel times and lockage times) of the vessels or the locks. The system is characterized by relatively low levels of use in the late winter and early spring months and relatively high levels of use in the mid and late summer months.

Finally, the nature of the seasonality evident in commercial tow use of the UMR system merits discussion at this point. Commercial towboats that elect to operate on the UMR system forego operating elsewhere in the inland navigation system during the periods that they do operate in the UMR system. These towboats clearly have alternative uses as evidenced by their continuing operations elsewhere in the inland navigation system during periods of adverse operating conditions in the UMR and the fact that when the UMR system is available and operating conditions are favorable some towboats opt to operate on the UMR only for limited periods of time. Consequently, the seasonality evident in system use is driven by not only by the physical operating conditions of the system, but also by the economic returns to operating in the system relative to the economic returns foregone by not operating elsewhere in the inland navigation system.

Effect of the Status of a Lock Chamber at the Arrival Time of a Vessel

Inspection of the detailed lockage time distributions suggests that the state of the lock chamber itself at the time of the arrival of a vessel, either occupied with an upbound lockage, occupied with a downbound lockage, or unoccupied, affects the lockage time of an arriving vessel. To explore this effect, three mutually exclusive lockage types are defined to characterize the status of a lock when a vessel arrives and is then ultimately processed through the lock. A “fly” lockage type for a vessel is defined as a lockage in which the lock is unoccupied when the vessel arrives at the lock and the vessel is the next vessel processed at the lock. A “turnback” lockage type for a vessel is defined as a lockage in which the lock is occupied when the vessel arrives at the lock, the arriving vessel must then wait for service in the lock queue, and when the vessel finally begins its lockage, the immediate prior vessel completing lockage is traveling in the same direction as the vessel beginning its lockage. Finally an “exchange” lockage type for a vessel is defined as a lockage in which the lock is occupied when the vessel arrives at the lock, the arriving vessel must then wait for service in the lock queue, and when the vessel finally begins its lockage, the immediate prior vessel completing lockage is traveling in the opposite direction as the vessel beginning lockage. The definitions of lockage types adopted here differ slightly from lockage type definitions typically adopted in Corps of Engineers publications where the terms fly, turnback, and exchange differentiate lock approaches and exits by vessels rather than differentiate complete types of lockages (see, for example, U.S. Army Corps of Engineers (2004), pages Econ 52-124). Consequently, there are more lockage types typically identified in Corps publications than the three lockage types identified here, however, the definitions adopted here have the virtue of focusing on the state of the lock chamber at the point in time when each vessel arrives at the lock or enters the lock as an individual lockage in a sequence of lockages.

Tables 11, 12, and 13 display selected summary statistics of the distributions of lockage times at the five UMR locks for multi-cut vessels, single cut vessels, and local vessels, respectively, characterized by the direction of travel of the vessel completing lockage and the lockage type as defined above. Tables 11 through 13 reveal that there is an important dependency between the observed lockage time of a vessel and the lockage type as defined above at each of these locks. At all locks and in both directions of travel, turnback lockages are on average significantly quicker than exchange lockages for multi-cut tows. This reflects the fact that a large, multi-cut, waiting tow moving in the same direction as the previous vessel completing lockage can begin its approach to the lock while the exiting vessel is still in the lock or exiting the lock. Large, waiting, multi-cut tows moving in the opposite direction as the previous vessel must wait for the exiting vessel to complete its entire exit before approaching the lock resulting in relatively lengthy lockage times. For similar reasons, observed turnback lockages for single cut tows are also significantly faster on average than exchange lockages at all locks in both directions with the sole exception of downbound single cut tow lockages at Lock 24. For both multi-cut and single cut tows, fly lockage types are on average associated with the longest lockage times at all locks. For local vessel traffic at the locks, turnback lockages are on average quicker than exchange lockages at some locks, exchange lockages are on average the fastest at other locks, and fly lockages are on average the fastest at still other locks.

As a caution, it should be noted that the Corps OMNI database appears to understate somewhat the total quantity of time needed to complete a turnback lockage at these five locks as there is almost always some positive interval of time between the start of lockage time recorded for the second vessel in the turnback sequence and the end of lockage time recorded for the first vessel. In fact, only 2.4 percent of the 23,004 turnback lockages identified in the OMNI data began prior to or at the end of lockage time recorded for the previous lockage. This interval of time averages approximately eight minutes per turnback lockage sequence, is tightly distributed around the mean with a standard deviation of about 10 minutes, and in most cases most likely reflects the time needed to cycle the empty lock chamber from the water level of the exiting tow back to the water level of the entering tow.

5. THE UMR SIMULATION MODEL

There is a rich and growing body of literature concerning the use of simulation models in analyzing waterways transportation networks that has its beginning with a report by Carroll (1972) and an article by Carroll and Bronzini (1973). These two early efforts laid the foundation for understanding the importance and use of simulation models in modeling inland waterway system operations. Fundamentally, inland navigation systems exhibit a sufficient degree of interdependent performance characteristics to limit the use of queuing theory tools or related analyses in faithfully capturing the behaviors evident in such systems. Later, beginning in the early 1990's, a series of articles documents the development of a sequence of various inland waterway simulation models designed to explore and evaluate an increasingly large range of operating issues and management policies (for examples, see Dai and Schonfeld (1991), (1992), and (1994); Kim and Schonfeld (1995); Martinelli and Schonfeld (1995): Ramanathan and Schonfeld (1994); Ting and Schonfeld (1996), (1998a), (1998b), (1999), (2001a), (2001b); Wang and Schonfeld (2002); Wei et al. (1992); Zhu et al. (1999)). These articles create and utilize many different simulation models to analyze various methods of scheduling and sequencing tows in attempts to reduce overall lock delay times and reduce water transportation costs.

However, all of the waterways simulation models created in this series of articles invoke two related simplifying assumptions that create distortions in the simulations when attempting to model the operation of the UMR navigation system. The first of these assumptions is that the navigation system being modeled achieves or approximates a steady state level of system performance. As the detailed examination of the Corps OMNI data described above makes clear, the UMR navigation system never achieves or approximates a steady state level of system performance. The lack of steady state performance of the UMR system is the direct consequence of the fact that the demands for both commercial and non-commercial use of the system vary significantly over time throughout each annual navigation season. The second of the simplifying assumptions invoked by prior waterway simulation models is that the demands for service placed on the system by individual tow movements are independent of each other and, consequently, the system trips generated by these demands are also independent of each other. The UMR navigation system segment north of Lock 25 is a closed loop navigation system with only a single link connecting the entire system north of Lock 25 to the remainder of the inland waterway system. At the conclusion of each annual navigation season nearly all of the waterway floating equipment operating north of Lock 25 completely exits the UMR system and operates elsewhere until the system reopens for the next navigation system. As a result, waterway transportation equipment must initially enter the UMR system each year with an upbound lockage at Lock 25 and again ultimately exit the UMR system each year with a downbound lockage at Lock 25. Therefore, to complete a specific origin to destination movement, the needed waterway equipment must either first move from some other location in the UMR to the origin of the movement or the needed waterway equipment must enter the UMR system as an upbound lockage through Lock 25 and then proceed to the origin of the movement. Consequently, origin and destination specific movements of tows cannot be modeled as independent of each other as the towboat and barges required to complete each movement must have been moved through the system at some earlier point in time either as new entrance to system or from the destination of a previously completed movement. Hence, the movements are dependent.

Based on the results of the analysis of the Corps OMNI data completed above, a stylized simulation model is formulated and constructed that simulates vessel and lock operations of the UMR navigation system segment extending from Lock 20 to Lock 25. The model simulates individual vessel movements at and between these locks for an entire calendar year. The model incorporates exogenous variables that influence vessel movement through the system such as total system traffic levels, differential operating characteristics of vessels, inter-dependence of lock processing times for vessels, and, most importantly, intra-seasonal variability of dependent demands for system use.

The basic logic underlying the simulation model created here is founded on the observed operations of the UMR system as recorded in the Corps OMNI data. The model begins the simulation year with a cold start in that very few tows are desirous of entering and using the system in the winter months. In the early spring, system use rapidly increases as more and more tows begin entering and circulating through the system. During the summer months the number of new tows entering and using the system is roughly balanced by the number of tows that exit the system and do not return to the system for the duration of the simulated year. In the fall months the number of system exits begins to gradually outweigh the new system entrances and, finally, in the winter months the number of system exits greatly outnumbers the number of new system entrances eventually culminating with nearly all tows exiting the system sometime during December. At all times throughout the simulation period, individual tow trips originating in the system cannot begin until a prior tow trip completes at that destination or a new tow enters the system destined for the origin of the originating tow trip.

A product of Micro Analysis and Design, Micro Saint 4.1, is employed to create the discrete-event UMR simulation model. The Micro Saint 4.1 software permits the simulation model to utilize an embedded feature entitled “Action View” to graphically present the movements of the vessels through the system on a scaled map on a PC display as the model executes. This visual feedback helps audiences unfamiliar with simulation models to literally watch the system operate during the simulated period of time and to observe changes in the system as they occur in simulation time. Figure 12 presents the scaled map created for the on-screen presentation of the UMR Simulation Model.

UMR Simulation Model Components

Micro Saint 4.1 based simulation models are constructed of “model components” that are related through a network diagram termed a “task network”. The two fundamental types of model components that define a task network are tasks and entities. Tasks represent related network activities. Entities “travel” through the network of related tasks. The paths that individual entities follow as they travel through the network are determined by supplementary model components. The important components of the waterway simulation model are described in more detail below. Detailed descriptions of the role and use of model components may be found in Micro Analysis and Design, Inc. (2002).

Entities

An entity is an object that travels through the network of tasks and indicates by its location in the network when each task is executing or waiting to execute. Each entity defined in the UMR simulation model represents a unique waterway vessel or a group of local vessels that pass through a lock simultaneously. There are three different categories of vessels defined in the simulation model: local vessels; small tows; and large tows. Local vessels represent all traffic at individual system locks that does not utilize any other system lock, small tows represent commercial tows with barges that move through the entire system and that can pass through each of the system locks in a single cut, and large tows represent commercial tows with barges that move through the entire system and that require a multi-cut lockage to pass through each of the system locks. Each system tow maintains its configuration as a large or small throughout the entire simulation period. The three groups of entities in the UMR simulation model are:

- Local Vessels;

These vessels include recreational boats, passenger boats, light boats, and government boats. Unlike commercial tows, these vessels arrive at a given lock in the system, lock through that lock in a given direction, and then do not reappear at that lock or any other system lock for relatively long and uncertain periods of time. Further, these vessels can and do lock through system locks in multiple vessel lockages. These vessels are more numerous in the system than are commercial tows. In the simulation model, these vessels (or groups of these vessels each comprising a single lockage) are independently generated by separate tasks for each combination of lock and direction of travel and then these vessels are terminated in the system after completing their one and only lockage at the lock where they were generated. Local Vessel arrivals are treated in the model as independent Poisson random variables by direction of travel, lock, and by month of arrival. Consequently, the time between local vessel arrivals (the inter-arrival time) by lock, direction of travel, and month of arrival are represented by independent exponential distributions whose means are extracted from the Corps OMNI database and entered as parametric inputs into the simulation model. Table 14 displays the mean number of local vessel arrivals by lock and direction for each month of the simulation.

- Small Tows;

These vessels represent commercial tows that are small enough (less than 600 feet in length) to fit completely in the 600 feet long chambers of each of the five locks. These vessels are processed through each of the locks in single cut lockages. These tows are introduced periodically into the system as upbound lockages at Lock 25 throughout the simulation year using a distribution of inter-arrival times at Lock 25 derived from the Corps OMNI database. Specifically, small tows are randomly introduced into the system through simulation time using the monthly inter-arrival patterns of small tows observed completing their first annual upbound lockage at Lock 25 in the OMNI data. These tows then circulate through the entire system, first upbound all the way through Lock 20 and then back downbound from Lock 20 through Lock 25. When they complete this roundtrip with a downbound lockage at Lock 25 they exit the system for a variable period of time and then reappear as an upbound small tow at Lock 25 to begin another system roundtrip. This process of generating interdependent roundtrips continues until the tows complete their final roundtrip journey of the year. The probability that any given completed roundtrip of a small tow is the terminal annual roundtrip of that small tow is estimated by computing from the historic OMNI data the percentage of all downbound small tow lockages at Lock 25 that do not result in a later return of that tow to Lock 25 as an upbound lockage. These probabilities of not returning to the system are adjusted monthly in the simulation model to reflect the historic patterns evidenced in the OMNI data.

- Large Tows.

These vessels represent commercial tows which are longer than 600 feet and therefore do not fit fully assembled in the 600 feet long chambers of each of the five locks. Therefore, these vessels must be processed through the locks in multi-cut lockages. Like small tows, these tows are introduced periodically into the system as upbound lockages at Lock 25 throughout the simulation year using a distribution of inter-arrival times at Lock 25 derived from the Corps OMNI database. Specifically, large tows are randomly introduced into the system through simulation time using the monthly inter-arrival patterns of large tows observed completing their first annual upbound lockage at Lock 25 in the OMNI data. These tows then circulate through the entire system, first upbound all the way through Lock 20 and then back downbound from Lock 20 through Lock 25. When they complete this roundtrip with a downbound lockage at Lock 25 they exit the system for a variable period of time and then reappear as an upbound large tow at Lock 25 to begin another system roundtrip. This process of generating interdependent roundtrips continues until the tows complete their final roundtrip journey of the year. The probability that any given completed roundtrip of a large tow is the terminal annual roundtrip of that large tow is estimated by computing from the historic OMNI data the percentage of all downbound large tow lockages at Lock 25 that do not result in a later return of that tow to Lock 25 as an upbound lockage. These probabilities of not returning to the system are adjusted monthly in the simulation model to reflect the historic patterns evidenced in the OMNI data.

Tags

A “Tag” is a Micro Saint “system” variable that records the unique identity of each entity when there are many entities traveling simultaneously through the task network. Tag values in the UMR simulation model are assigned to small and large tows at the beginning of the simulation and to local vessels as they are generated. Once a vessel is assigned a tag value, the value stays with the vessel through the entire simulation.

Tasks

Tasks are the fundamental building blocks of a Micro Saint 4.1 simulation model network. A task is characterized by its execution time distribution, the constraints that limit its execution, the effect of its execution on other tasks, the effect of its execution on variables of interest defined for the system, and the effect of its execution on related subsequent tasks. The tasks in a Micro Saint 4.1 simulation model are connected by a “task network” which defines how tasks are related to each other and under what conditions tasks are to be completed. The tasks defined in the task network of the UMR simulation model are:

- Fill the lockage time distribution arrays with means and standard deviations;

This task is defined to enter the means and standard deviations of lockage time distributions for each lock (20, 21, 22, 24, and 25), by each vessel type (Local, Small Tow, Large Tow), by each direction of travel (Upbound, Downbound), and by each lockage type (Fly, Exchange, Turnback). The mean lockage times and standard deviations of these distributions are displayed in Tables 11, 12 and 13. Lognormal random variables are used to represent the underlying distributions of the realized individual lockage times. This task executes only once at simulation time zero and requires no simulated time to complete.

- Fill the pool transit time distribution arrays with means and standard deviations;

This is a task defined to enter the means and standard deviations of pool transit time distributions for each pool (20, 21, 22, 24), by each vessel type (Small Tow, Large Tow), and by each direction of travel (Upbound, Downbound). The transit time is the time required by a system tow to move from one lock to the next. Note that only tows transit the pools in the model to another lock and that each tow maintains a constant but randomly chosen speed for each transit of a lock pool. Local vessel traffic originates and terminates at each lock separately. The mean pool transit times and standard deviations of these distributions are contained in Tables 9 and 10. Lognormal distributions are used to represent the underlying distributions of the realized pool transit times. This task executes only at simulation time zero and requires no simulated time to complete.

- Fill the local vessel inter-arrival time distribution arrays with means;

This is a task defined to enter the mean inter-arrival time between local vessel traffic arrivals for each lock (20, 21, 22, 24, and 25) by simulation month (1 through 12) and by each direction of travel (Upbound, Downbound). The inter-arrival time distributions are assumed exponentially distributed in each simulation month for each system lock by each direction. Consequently, mean inter-arrival times do not vary within a simulated month, but do vary from month to month during the simulation of an entire year. Micro Saint 4.1 requires only the mean value of exponential random variables associated with task executions which is the reason why only the mean value is entered into the parameter array. The mean inter-arrival times for local vessel arrivals by lock and month are displayed in Table 15. This task executes only at simulation time zero and requires no simulated time to complete.

- Fill the new tow entrance inter-arrival time distribution arrays with means;

This is a task defined to enter the mean inter-arrival time between new tow entrances into system upbound at Lock 25 for the first annual transit of the system by each tow type (Large and Small) by simulation month (1 through 12). The inter-arrival time distributions are assumed exponentially distributed in each simulation month for each type of tow. Consequently, mean inter-arrival times do not vary within a simulated month for each type of tow, but do vary from month to month during the simulation of an entire year. Micro Saint 4.1 requires only the mean value of exponential random variables associated with task executions which is the reason why only the mean is entered into the parameter array. This task executes only at simulation time zero and requires no simulated time to complete.

- Fill the terminal system exit probability distribution arrays with means;

This task defines the probability that a downbound tow completing a lockage at Lock 25 does not return later in the simulation period to reuse the system again. These probabilities of not returning are characterized by tow type (Large and Small) and simulation month (1 through 12). Table 17 displays these probabilities. This task executes only at simulation time zero and requires no simulated time to complete.

- Define the prioritization values for the queue dispatch policy at each lock;

This task sets the priority values used by the simulation model to select a vessel to begin its lockage at a lock from the associated queue of waiting vessels. These priorities differ by lockage type, vessel type, and lock. This task executes only at simulation time zero and requires no simulated time to complete.

- Create and display the on-screen map for the model animation;

This task displays a map of the UMR system on the PC monitor and defines the variables to be displayed on the map as the simulation executes. The variables defined for display are updated in simulated time as the model executes. This task executes only at simulation time zero and requires no simulated time to complete.

- Create the tags to track small tows as they move through the system;

Tags are Micro Saint internal variables defined to track and identify entities moving through the task network. This task creates a pool of tag values to be associated with small tows. This task executes only at simulation time zero and requires no simulated time to complete.

- Create the tags to track large tows as they move through the system;

Tags are Micro Saint internal variables defined to track and identify entities moving through the task network. This task creates a pool of tag values to be associated with large tows. This task executes only at simulation time zero and requires no time simulated to complete.

- Introduce a small tow into the system;

This task introduces a new small tow into the system for its initial annual upbound lockage at Lock 25. This task then reschedules itself to execute again dependent upon the inter-arrival time distribution for small tows introductions into the system for the current month of the simulation. This task executes repeatedly during the simulation.

- Introduce a large tow into the system;

This task introduces a new large tow into the system for its initial annual upbound lockage at Lock 25. This task then reschedules itself to execute again dependent upon the inter-arrival time distribution for large tows into the system for the current month of the simulation. Table 16 displays the mean inter-arrival arrival times for the introduction of small and large tows by simulation month. This task executes repeatedly during the simulation.

- Begin local vessel arrivals;

This task signals the ten tasks that schedule local vessel arrivals at the locks to begin to schedule local vessel arrivals. This task executes only at simulation time zero and requires no simulated time to complete.

- Lock a vessel through a lock;

There are five separate lockage tasks included in the “task network”, one each for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25. Each of these tasks represents the completion of a unique lockage at a lock. The time to complete each of these lockage tasks is characterized by a lognormal distribution whose mean and standard deviation vary by vessel type (Local, Small Tow, Large Tow), by direction of travel (Upbound, Downbound), and by lockage type (Fly, Exchange, Turnback). The lognormal distribution is a pre-defined distribution in the Micro Saint 4.1 software characterized by its mean and standard deviation. The lognormal distribution is a reasonable approximation for tasks that cannot be completed much faster than the mean but sometimes take much longer than the mean to complete. This distribution is an appropriate approximation for tasks with no practical upper bound on their time duration, but for which very long completion durations are relatively rare occurrences. The sensitivity of the model to the use of lognormal distributions to characterize the performance of these and other similar tasks was explored by replacing the lognormal distributions with gamma distributions with identical means and standard deviations. The gamma distributional forms produced fewer extreme values in executing the individual tasks in the model than did the lognormal distributional forms, but did not, however, significantly alter the ability of the model to reasonably replicate the observed operations of the IMR system.

The mean lockage times and standard deviations of these lognormal distributions are displayed in Table 8. These lockage tasks can only each execute when the lock is unoccupied. Any vessels arriving at a lock for lockage during a period when the lock is occupied enter a queue to await the later availability of the lock. Local vessels are given first priority in the queue for selection for lockage over tows. Tows are prioritized on a First In, First Out basis. This queue dispatch policy is adopted in the model to reflect the fact that the largest portion of local vessel arrivals observed at these locks is composed of recreation vessels that are given priority in the real UMR lockage queues. When a vessel completes its lockage it is routed into the immediate upstream or downstream pool dependent on its direction of travel and then begins the task of moving through that pool to the next system lock. These lockage tasks execute repeatedly as needed and require simulated time to execute.

- Move a vessel through a pool;

There are four separate pool transit tasks included in the task network, one each for Pool 21, Pool 22, Pool 24, and Pool 25. Each of these tasks represents the movement of a single vessel from a lock to another lock for processing at the next lock. The time to complete each of these pool transit tasks is characterized by a lognormal distribution whose mean and standard deviation vary by vessel type (Small Tow, Large Tow) and by direction of travel (Upbound, Downbound). The mean pool transit times and standard deviations of these lognormal distributions are displayed in Tables 9 and 10. These tasks execute whenever a vessel enters a pool after completing a lockage. Multiple vessels can be moving in the pool simultaneously and may pass each other in moving to the next lock. These tasks execute repeatedly as required during model execution.

- Change the direction of travel of a tow;

There are two tasks that change the direction of travel of a tow in the system. The first task that changes the direction of travel of a tow executes when a tow completes an upbound lockage at Lock 20. The duration of time that it takes for a tow to change direction north of Lock 20 and then return to Lock 20 as a downbound tow is represented as a lognormal distribution whose mean and standard deviation are dependent on the vessel type (Small Tow, Large Tow). This task in the model represents the time spent by commercial tows in activities in the UMR navigation system north of Lock 20. Multiple vessels can be engaged in this task simultaneously and may pass each other when returning to Lock 20 as a downbound tow. This task is executed repeatedly as required during the model execution.

The second task that changes the direction of travel of a tow executes when a tow completes a downbound lockage at Lock 25. The duration of time that it takes for a tow to change direction somewhere south of Lock 25 and then return as an upbound tow at Lock 25 is represented as a lognormal distribution whose mean and standard deviation are dependent on the vessel type (Small Tow, Large Tow). This task represents the time spent by tows during the simulation in activities anywhere in the inland navigation system south of Lock 25. Multiple vessels can be engaged in this task simultaneously and may pass each other when returning to Lock 25 as an upbound tow.

Not all downbound tows exiting Lock 25 return to Lock 25 as upbound tows as some downbound tows will exit the system for the remainder of the calendar year. This phenomenon is represented in the model by having this return task only execute based on the observed probability (adjusted monthly) that a tow completing a downbound lockage at Lock 25 returns to the UMR system to complete another roundtrip. The probability of returning to the system varies by simulation month and vessel type (Small Tow, Large Tow). Early in the simulation year almost all tows do return to the system after a downbound lockage and do complete another roundtrip. As the simulated year progresses a greater and greater proportion of tows do not return to the system and by December nearly all tows do not return to Lock 25 to attempt to complete another roundtrip. This task is executed repeatedly as required during the model execution.

Note that by defining only these two tasks where tows change their direction of travel through the system all tows are required in the model to complete an entire roundtrip of the system before exiting the system in a downbound lockage at Lock 25. In the real UMR system tows can and do change not only their direction of travel but also their flotilla at various locations between Lock 20 and Lock 25. The Corps OMNI data indicates that most large tows (over 90% of all large tows) do traverse the entire length of the five lock system as large tows without changing their direction of travel between Lock 20 and Lock 25, but that the majority of small tows do change their flotilla and direction of travel somewhere between Lock 20 and Lock 25. Fortunately, most of the small tows that do change their flotilla and direction of travel do so in Pool 22 and, further, do so in a roughly balanced manner from an upbound small tow to a downbound small tow and vice versa. Consequently, treating all tows as traversing the entire system will not dramatically distort the simulation of the system of locks and permits the use of roundtrips completed as a simple and useful measure of the production of the system.

It is straightforward to alter the model to incorporate more complex and realistic tow behavior; however the Corps OMNI database does not record the actual activities of tows between arrivals at locks and consequently it is not possible to identify precisely where and how a tow changes configuration or direction in a pool. Further, forcing all tows to transit the entire five lock system upbound and then downbound permits a simple and easy to understand measure of the output produced by tows using the system: the number of roundtrips completed per unit of time. Consequently, absent detailed information regarding actual tow behavior in the pools, all tows in the simulation model are required to transit the entire five lock system in each direction to complete a roundtrip. If detailed information regarding tow behavior in the pools becomes available then the measure of output could be redefined to more customary measures such as total tow-miles produced, total barge-miles produced, total loaded-barge miles produced, or total ton-miles produced to better measure the productivity of the tows in the system. The framework of the UMR simulation model can readily incorporate this more complex tow behavior. These tasks execute repeatedly as required during model execution.

- Schedule a local vessel arrival at a lock;

There are ten separate local vessel arrival tasks included in the task network, two each (Upbound, Downbound) for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25. Each of these tasks creates the arrival of a local vessel at a lock and then reschedules itself to execute again dependent upon the inter-arrival time distribution for local vessels. The inter-arrival time is characterized by an exponential distribution whose mean for each lock and direction of travel varies by month. The mean lockage times and standard deviations of these distributions are displayed in Table 15. These tasks execute repeatedly during model execution.

- Record data for the completion of local vessel lockages;

There are five separate tasks included in the task network, one each for Lock 20, Lock 21, Lock 22, Lock 24, and Lock 25 to record information regarding the local vessel lockages completed at the system locks. These tasks are executed whenever a local vessel completes lockage at a lock. When a local vessel completes its lockage it is routed to this task and the local vessel is terminated in the system and information regarding its lockage is recorded. These tasks execute repeatedly during model execution and consume no simulated time to execute.

- Record data for the movement of tows through the system.

This task is designed to collect data regarding the movement of vessels through the system. This task executes every time a small or large tow completes a roundtrip of the system and requires no simulated time to execute.

Task Queues

In a Micro Saint 4.1 model, a queue is a waiting area associated with a network task where entities (vessels) accumulate while they are waiting to execute the task. An entity can only execute a task when the “release condition” for executing that task is met. If an entity arrives at a task in the network and the release condition for that task is not met, then the entity enters the queue associated with that task and waits with all other entities that are in the queue for a release to begin executing that task. Each time the release condition for the task becomes true, an entity is selected from the queue to begin execution of the task.

In the UMR simulation model, queues are associated with each lock task. In the model only one lockage may be executing at each lock at any given time. Vessels enter the lock queue only if the lock is occupied by another vessel when the vessel arrives. The lock queues are assumed to have unlimited storage for vessels waiting for lockage. A waiting vessel is released from the queue when the vessel occupying the lock completes its lockage. Vessels are selected from the pool of vessels waiting in the queue to begin lockage by a queue dispatching policy. Each lock queue has a dispatching policy that utilizes a built in prioritization rule, such as FIFO or LIFO, or a customized priority rule. The UMR simulation model implements a customized dispatch policy in which local vessels are given first priority in the queue for completing a lockage over both small and large tows. Tows are prioritized after local vessels on a first in, first out basis. This queue dispatch policy is adopted to reflect the fact that the largest portion of local vessel arrivals observed at these locks is composed of recreation vessels which are given priority in the real UMR lockage queues and that for the vast majority of time the UMR operates as a FIFO system for all arriving tows at locks.

Decision Nodes

A decision node is automatically created in the Micro Saint 4.1 task network whenever a task has more than one possible path leading to subsequent tasks. There are three different decision types that may be associated with each decision node in a task network: a tactical decision, a probabilistic decision, or a multiple decision. The decision type determines the path or paths that an entity (vessel) will follow upon completion of a given task when more than one path is available. In a tactical decision type, the task with the tactical expression that evaluates to the highest value in the routing condition field of the Decision Node executes next. In a probabilistic decision type, only one of the following tasks executes next. The probability that a particular task follows is equal to its probability value in the routing condition field of the Decision Node. In a multiple decision type, all of the following tasks with nonzero routing conditions begin execution simultaneously following execution of the current task. When this happens, the entity exiting the current task splits into multiple entities, one for each following task. These entities all retain the same tag value.

In the UMR simulation model, an important probabilistic decision node is reached upon completion of a downbound tow Lockage at Lock 25. This node determines if the tow is rescheduled to re-enter the system at a later time, or if instead the tow has completed its final use of the system for that simulation year. The entities section above contains details on how these probabilities are estimated and used. There is also a tactical decision node encountered immediately upon the completion of each lock and each pool task that is used to move the vessel completing the task to the appropriate next task based upon vessel type and direction of travel.

Variables

Micro Saint 4.1 permits definition of variables designed to track the performance of the simulation network, the movement of entities through the network, and record other quantities of interest as the model executes. The variables included in the model may also be structured to influence or alter the execution of tasks and the sequence of tasks to be executed. Table 18 presents a complete listing and description of the variables defined for the UMR Simulation model.

Snapshots

Micro Saint 4.1 permits the model to schedule “snapshots” of variables of interest at pre-determined times or intervals to record the values of designated variables as the model is executing. These snapshots serve to record the dynamics of the system as it changes through simulation time. There are two snapshots defined in the UMR Waterway Simulation model, an end-of-run snapshot and a periodic snapshot which records the status of selected variables every 730 hours of simulation time. The periodic snapshot is designed to permit an examination of the dynamics of the simulated system in twelve intervals of approximately one month’s duration each. These periodic snapshots facilitate the comparison of the simulated system to the monthly summaries of the operation of the real system compiled from the Corps OMNI data. Table 19 displays the variables recorded in each of these snapshots.

Event Queue

The Micro Saint 4.1 Event Queue contains a list of events termed “scenario events”. Scenario events provide a method to cause certain events to occur at specified times during the execution of the model. These events can be one-time events, or they can represent events that repeat at defined intervals. Scenario events are used to change variable values and thereby change the state of the model when the event occurs. Scenario events assign values to variables independent of when an entity begins or ends a task or enters or departs a queue. The Event Queue is used in the UMR Simulation Model to alter the simulation month as time in the simulated year progresses. This facilitates changes in the task execution time distributions that are sensitive in the model to the time of the year when the task executes. The Event Queue can also be used to schedule other system altering events such as periods of decreased lock performance or periods of complete lock unavailability.

The Task Network

The task network of the UMR Micro Saint 4.1 simulation model is composed of two main groups of tasks. The first group of tasks is comprised of tasks that execute only once when the model is launched and that require no simulation time to execute. These tasks populate variables with initial values, define the probability distribution parameters required for the execution of other tasks, and create the scaled map for displaying the model animation. Detailed descriptions of these tasks are presented above.

The second group of tasks forms the core of the model and is composed of tasks that simulate the movement of vessels through the UMR system. These tasks do consume simulation time to move vessels through the system. The variable quantities of simulation time required to complete these tasks are determined each time these tasks are executed by independent random draws from their associated probability distributions. These tasks schedule vessels to enter the system, move vessels through the locks and the pools of the system, and ultimately schedule vessels to exit the system or return to the system at a later time. The remainder of this section focuses on this portion of the task network that is the core of the simulation model. Figure 13 displays a schematic diagram depicting the relationships of these core tasks.

After the initial group of set-up tasks completes the simulation of vessels movements begins. As shown in Figure 13, individual tows first enter the system to begin an initial roundtrip through the system with an upstream lockage at lock 25. On each tow's initial entrance to the system the tow is defined as a large or small tow and the next initial tow entrance for that type of tow is scheduled. The characteristics (large or small) of each tow do not change over the course of the entire simulation. The mean times between initial tow entrances change monthly during the course of the simulated year to capture the seasonality of when tows first enter the system.

Each tow then travels through the entire upbound sequence of five locks and four connecting pools. The time required to complete each of these tasks is drawn at the beginning of the execution of each separate task from the probability distribution associated with the completion of that task for a tow with the appropriate characteristics. Only one vessel may be processed through each lock at any given time and vessels arriving at an already occupied lock are forced to wait in that lock's queue until the lock is unoccupied and the vessel is selected for processing by the queue dispatch policy. Both lock queues and system pools have unlimited capacities. Tow transit times through the pools are not impacted by other vessels using the pools and are drawn from probability distributions that reflect the characteristics of the tow.

When each tow completes the upbound leg of its roundtrip with an upbound lockage at Lock 20 it is then scheduled to reappear in the system at a later time as a downbound lockage at Lock 20 to begin the downbound leg of the roundtrip. The tow then travels through the entire downbound sequence of locks and connecting pools until it completes its roundtrip with a downbound lockage at Lock 25. Then the tow is either rescheduled to appear at a later time as an upbound lockage at Lock 25 or the tow exits the system without returning for the duration of the simulation year. The probability that a tow does not return to the system when completing a roundtrip changes monthly to reflect the seasonality of tows exiting the system.

In contrast with tow movements through the system, local vessels arrive at each lock in both upbound and downbound directions independently. The time between the independent arrivals changes monthly to reflect the seasonality of local vessel use of each lock. If the lock is occupied when a local vessel arrives at a lock the local vessel is forced to wait in that lock's queue until the lock is unoccupied and the vessel is selected for processing by the queue dispatch policy. When the local vessel completes its lockage the local vessel is removed from the system and the lock becomes available to process the next vessel. Local vessels do not travel through the entire system, but rather only transit a single lock.

6. EVALUATION OF THE UMR SIMULATION MODEL

This section presents an evaluation of the performance of the UMR simulation model in accurately depicting the operation of the UMR system as represented in the Corps OMNI database and then presents an example application of the model to estimate the changes in the operation of the system resulting from implementing an alternative lock queue dispatch policy for system tows.

Evaluation and Calibration of the UMR Simulation Model

Table 20 presents selected summary statistics compiled from the Corps OMNI database for UMR Locks 20 through 25 from 2000 through 2003 regarding the annual total number of lockages, the annual total of vessel wait time for lock service, the annual total of vessel lockage time, the mean wait for service time for all vessels, and the mean lockage time for all vessels. Table 21 presents the same selected summary statistics reclassified by vessel type as defined in the UMR simulation model. The information presented in these two tables serves as the benchmark to measure, calibrate, and evaluate the performance and of the Micro Saint 4.1 UMR navigation system simulation model.

It is very likely that tows as represented in the simulation model will outperform real UMR tows for two reasons. The first reason is that the variability of tow performance in completing lockages and pool transits in the simulation model is represented by independent draws from lognormal probability distributions characterized by the means and standard deviations of vessel and lock performances compiled from the Corps OMNI data. These distributions will under represent the probability of rare, but observable in the data, extraordinarily poor vessel and lock performances. For example, as described in detail above, there were some extraordinarily poor lock performances recorded at Lock 25 in May of 2001 that are unlikely to be represented appropriately as the result of random draws from the lognormal distribution that represents these lockages in the model.

The second reason that tows in the model will outperform their real UMR counterparts is that the tows in the simulation model all complete at least one roundtrip of the entire system before potentially exiting the system for the duration of the simulated year as a downbound lockage at Lock 25. Examination of the Corps OMNI data indicates that an average of 232 individual tows per year produced an average total of 13,633 small and large tow lockages per year at these five locks. Of these 232 unique tows per year only an average of 186.75 per year produced at least 10 lockages in the five lock system in any given year. Consequently, an average of 45.25 individual tows in each year recorded less than 10 lockages at these locks. In the simulation model each large or small tow that enters the system must produce at least 10 lockages before it can exit the system and, therefore, tows in the simulation model will on average produce more annual lockages than a significant portion of their real UMR system counterparts.

One important dimension of the operations of real tows at these five locks warrants discussion at this point: when viewed from the perspective of the total time available of tows that do operate on this segment of the UMR, the proportion of time spent by tows waiting for lockage or locking through these five locks is very small. As discussed just above during the period from 2000 through 2003, an annual average of 232 unique tows operated on some portion of this five lock segment of the UMR. These 232 tows represent an annual average of 2,032,320 available tow hours. Table 21 indicates that an average of 40,587 of these available hours were used waiting for lockage at these locks and 23,465 of these available hours were used locking through these locks. Therefore, only 2.0 percent of the available time of these 232 tows is spent waiting for lockage through these five locks and only 1.2 percent of the available time of these 232 tows is spent locking through these five locks. Stated equivalently, 96.8 percent of the total annual available time of these tows is utilized in activities other than those directly related to locking through these five locks. Consequently, any policy designed to alter the operating conditions or performance characteristics of these five locks can have only a very small impact on the total productivity of tows operating in the UMR system.

Table 22 presents selected summary statistics compiled from the initial results of 100 simulated years of system operation by the UMR simulation model. As expected the simulated tows represented in the model do appear to outperform real UMR system tows. An average of 219.6 simulated tows produces at least one roundtrip per year through the system of five locks. The simulated tows complete an average of 1,423.7 roundtrips per year with a sample standard deviation of 123 roundtrips. As each simulated roundtrip requires 10 lockages, the simulated tows produce an average of 14,237 lockages which is 604 more lockages per year than the average of 13,633 lockages per year produced by real tows during the period from 2000 through 2003. Of these 100 simulations, 69 simulations produced more system tow lockages per year than the historic average.

The over performance of the individual tows as represented in the simulation model creates lock wait times and utilization rates in the model that are also greater than those observed during this period in this segment of the UMR system. In the UMR simulation model, vessels wait an average of 52,278 hours per year for lock service and utilize 26,561 hours of lock time per year completing lockages at these five locks. The corresponding averages compiled from the Corps 2000-2003 OMNI data are 42,118 hours and 24,656 hours, respectively. Further, the mean simulated wait for service and lock utilization times are greater for each of the five locks individually than those compiled from the historic Corps data.

Two parameters are provided in the simulation model for the purpose of altering the expected number of tows that operate in the simulated system. These two parameters proportionately alter the monthly mean inter-arrival times for large and small tow initial entrances to the simulated system, respectively. These parameters are designed to preserve the monthly seasonality of initial tow arrivals in the system while permitting the total expected number of large or small tows operating in the simulated system to vary. Increasing the mean inter-arrival time decreases the expected number of tows and, conversely, decreasing the mean inter-arrival time increases the expected number of tows. These parameters provide a simple mechanism for calibrating the simulation model to known conditions and also provide a mechanism to examine the system response to different expected annual tow demands on the system.

As discussed above, the 2000-2003 Corps OMNI data indicate that an average of 42.25 individual tows per year operating at these five locks produced less than ten lockages in a given year and an average of 186.75 individual tows per year produced at least ten lockages. The data also indicates that the 42.25 tows that produced less than ten lockages in a given year were responsible for an average of 210.25 lockages in that year. In the simulation model this represents the minimal annual production of an average of 21.02 tows. Hence, a minimum of 208.77 simulated tows (equal to the sum of the 186.75 tows plus the 21.02 tows) will be required on average to represent the production of the 232 real system tows. Table 22 indicates that an average 219.6 tows per year entered the simulated system and produced at least one roundtrip. Therefore, increasing the mean time between initial tow arrivals into the simulated system by approximately five percent will decrease the expected number of tow entrances to the system by approximately five percent and the simulated system's expected production to levels that more closely approximate the observed production levels of real tows in the UMR system for the period 2000 through 2003.

Table 23 displays the results of 100 annual UMR simulations incorporating this five percent increase in the mean time between initial tow arrivals in the system. Increasing the mean inter-arrival time between initial tow entrances to the system by five percent decreases the sample mean number of tows that operate in the system to 209.2 with a sample standard deviation of 17.0 and the mean number of annual roundtrips completed by the simulated sample of tows to 1,364.3 with a sample standard deviation of 117.9 roundtrips. Of these 100 simulations, 54 simulations produced more system tow lockages per year than the historic average of 13,633 lockages.

In the modified UMR simulation model, Table 23 indicates that an average of 17,438.5 vessels wait an average of 41,199.3 hours per year for lock service and utilize an average of 25,855.8 hours of time per year completing lockages at these five locks. The corresponding averages compiled from the Corps 2000-2003 OMNI data are an average of 17,545 vessels wait an average of 42,118 hours per year for lock service and utilize an average of 25,390.8 hours of time per year (including chamber turnback time) completing lockages at these locks. The UMR simulation model adjusted to reflect the greater productivity of simulated tows relative to real tows clearly provides a more accurate simulation of the total level of vessel activities in this segment of the UMR than does the simulation model without the productivity adjustment.

An additional 500 annual simulations were performed using the calibrated UMR system model to investigate the stability of the simulation model. Table 24 presents selected detailed information compiled from the total of 600 model runs and compares the detailed results to the same statistics compiled from the 2000-2003 Corps OMNI data. Both at the system and individual lock level, the simulation model tracks observed average annual system productivity remarkably well. The mean total number of simulated lockages per year is within 0.4 percent of the observed total number of lockages per year and the mean number of simulated lockages per year at each of the locks is within 1.1 percent of the observed number of lockages per year. The simulation model does equally well at the system level in tracking the observed average annual wait for lockage times and lock utilization times. The mean simulated total wait for lockage time by all vessels is within 0.1 percent of the observed average annual wait for lockage time and the simulated mean total lockage time of all vessels is within 1.7 percent of the observed average annual total lockage time of all vessels. The simulation model also tracks the performance of commercial tows extremely well. The mean total number of simulated commercial tow lockages per year is within 0.3 percent of the observed total number of lockages per year. Finally, Table 24 indicates that a simulated tow requires an average of 525.9 hours, approximately 22 days, to complete a roundtrip and that simulated tows spend 2.4 percent of their available time waiting for lockage through these five locks, 1.4 percent of their available time locking through these five locks, and 96.2 percent of their total available time in activities other than those directly related to locking through these five locks. The simulated allocation of tow time between these activities tracks very well with the observed means in the OMNI data of 2.0 percent, 1.2 percent, and 96.8 percent, respectively.

Figures 14 through 17 explore some important dynamic properties of the simulated UMR system. Each figure presents a graphic in which the simulated year is portioned into twelve consecutive 730 hour long intervals. Each of these intervals approximately represents a simulated month of system activity. The intervals are labeled by their endpoints and the values displayed in each of the figures are compiled separately over each interval. Figure 14 presents the average amount of time in each of these twelve intervals that is utilized by vessels completing lockages in the system. Figure 15 depicts the average amount of time in each of the twelve intervals that are spent by vessels waiting for lockage in the system. Figure 16 depicts the average number of system lockages that are completed in each of the twelve intervals and Figure 17 displays the total number of tows that are operating in the system during each of the twelve intervals.

The seasonality evident in the real UMR system is also clearly present in these summary figures that represent the dynamics of the simulation. Like the real system, the simulated system displays very low demand for lockages and very little congestion in the first two simulated months. In the third simulated month the system begins to ramp up and the number of lockages completed and the resulting congestion evident at the locks significantly increases. The level of system use continues to increase as the simulation progresses until the number of lockages and resulting congestion peak during the eighth simulated month. After the peak there is a gradual and regular decrease in vessel use evidenced in the fall simulation months. In the final simulation month the vessel use dramatically decreases to the very low levels evidenced in the first two simulated months. The simulated UMR system replicates the seasonal dynamics present in the real UMR system with remarkable accuracy.

As discussed above, one consequence of the seasonality of vessel traffic movements in the real UMR system is the observable interdependence of lock operating conditions as revealed by the significant correlations between wait for lockage times at locks sequentially transited by tows. While there is no direct mechanism provided in the simulation model to measure the corresponding correlations between simulated sequential lock transit wait times by individual tows, Table 25 presents the Bivariate Pearson correlation coefficients computed for the number of vessels waiting for lockage in each of the five simulated lock queues as observed at the point in simulation time when the periodic monthly snapshots are recorded during each of the system simulations. The significant and positive correlations between all simultaneous lock queue sizes displayed in Table 25 indicates that the real interdependence of UMR lock operating conditions is preserved in the simulation model. The number of vessels in each lock's queue recorded by these snapshots is most highly correlated with the number of vessels in the queue of its nearest lock neighbors.

Finally, the very small sample standard deviation of the number of roundtrips produced in the UMR simulation model measured relative to the mean total number of roundtrips produced merits discussion. The sample coefficient of variation for the 600 annual simulations of the annual number of tow roundtrips completed is less than 0.09. This very low coefficient of variation indicates an extremely stable simulated system. This is quite remarkable considering the very large relative variability present in the completion of some individual system activities such as pool transit which have individual coefficients of variation of up to 8.4. The annual stability of the performance of the system is even more remarkable in light of the high degree of seasonality evident in the demand for system use. The primary determinant of annual productivity of the simulated system appears to be quite simply the number of tows that operate in the system rather than the inherent variability of the operating characteristics of the tasks that define the system. Figure 18 presents the relationship between the number of roundtrips completed and the number of tows operating annually in the simulated system. The Bivariate Pearson correlation coefficient for the number of roundtrips completed and the number of tows operating annually in the simulated system is significantly different from zero and equal to 0.888. This very strong correlation implies that the largest determinate of the annual productivity of the simulated system is the number of tows that operate in the system rather than the variability of the movements of the tows through the system.

An Application of the Model

In a series of articles Ting and Schonfeld (1996, 1998b, 2001a, 2001b) evaluate the effect of selected queue dispatch, vessel speed control, and integrated traffic control policies on the performance of various real and hypothetical segments of the inland waterway systems using simulation models. Ting and Schonfeld (1996) first simulate a system consisting of a single lock and evaluate variations of two alternative queue dispatch polices labeled SPF, shortest processing time per barge first, and SAVE, maximum processing time savings first when the single lock has multiple chambers. They find that both policies and their variations outperform a FCFS, first-come-first served, queue dispatch policy for single lock systems. The simulation model they base their finding on is a steady state model with independent vessel arrivals in each direction at the single lock.

Ting and Schonfeld (1998) extend their earlier investigation of alternative queue dispatch policies to a simulated system consisting of four linearly connected inland waterways locks with common traffic and evaluate traffic control policies integrated between the four locks. They find that the simulated system performs more efficiently when individual lock queue dispatch policies are coordinated between all the locks in the simulated system. The simulation model that they base these finings on is a steady state model with independent vessel arrivals at both endpoints of the linearly connected system of locks.

Ting and Schonfeld (2001a) return to a single lock simulation model when they evaluate a modified SPF policy, labeled FSPF, which implements an SPF policy that is amended to incorporate "fairness" considerations that places limits on the number of times each vessel can passed over in a SPF based lock queue dispatch policy. They find that FSPF still performs better than FCFS for various traffic levels at the lock without introducing the possibly large inequities present under heavy traffic loads in a fully implemented FPS queue dispatch policy. Here again, the simulation model they base their finding on is a steady state model with independent vessel arrivals in each direction at the single lock.

Lastly, Ting and Schonfeld (2001b) evaluate the impacts on tow operating costs of implementing queue dispatch policies including chamber packing policies, vessel speed control policies, and integrated policies in a single lock system with possibly multiple chambers at the single lock. They find there are reductions in tow operating costs associated with implementation of various combinations of these control alternatives as integrated control policies compared to FCFS without chamber packing and vessel speed control. Once again, the simulation model they base their findings on is a steady state model with independent vessel arrivals in each direction at the lock.

These articles establish a solid foundation for the use of simulation models in evaluating alternative queue dispatch and traffic control policies. The UMR simulation model presented here builds on and extends these earlier simulation models of individual locks and systems of locks by incorporating seasonal and interdependent traffic demands for specific origin and destination trips into the system simulation. Each of the previously discussed simulation models presumes non-seasonal and independent origin and destination specific traffic demands and, therefore, examines the steady state properties of the simulated locks or systems. As the evidence of seasonality in the Corps OMNI UMR data analysis presented above makes clear, the UMR system never achieves the characteristic properties of the operation of a steady state system. Hence, the UMR simulation model presents an opportunity to investigate the effects of traffic control policies under conditions of seasonal and interdependent traffic demands for specific origin and destination trips.

In the UMR simulation model tows arrive at system locks characterized by direction of travel, upbound or downbound, and by size, large or small. A simple and easy to implement queue dispatch policy whenever a queue forms at a lock is: (1) Local vessels move immediately to the head of the queue in the order that they arrive and, if there are no local vessels in the queue, (2) Tows waiting in the queue are prioritized by their expected lockage time at the lock as if each tow was the next to be dispatched for lockage and then the tow with the smallest expected processing time is dispatched from the queue when the lock becomes available. Since there are only eight possible combinations of lockage types (turnback or exchange), tow sizes (small or large) and directions of travel (upbound or downbound) that characterize potential tow lockages when selecting a tow from a queue it is a straight forward exercise to assign a priority to each tow in the queue and to identify the tow (or tows) with the fastest expected processing time in the queue. Ties for the fastest expected processing time may be decided by any decision rule, but breaking ties by order of tow arrival preserves the perception of equity in the dispatch policy and is adopted here for this dispatch policy. This queue dispatch policy will strongly favor small tows when selecting a tow for lockage from a lock queue, given the fact that the expected lockage time of any small tow is less than the fastest lockage time of any large tow at each system lock. Further, this queue dispatch policy is very nearly a locally implemented SPF tow dispatch policy as described in Ting and Schonfeld (1996) for each of the five UMR locks in the simulation model whenever small tow roundtrips are valued equal to or greater than large tow roundtrips.

Table 26 presents selected summary statistics compiled from the results of 600 annual simulations using the UMR model with the implementation of this local SPF queue dispatch policy at each of the five system locks. The implementation of this queue dispatch policy has a relatively small and subtle impact in the simulated UMR system when compared to the summary statistics for the simulated system with the existing queue tow dispatch policy displayed in Table 24. The mean number of lockages produced by all vessels annually in the simulated UMR system increases by 57 lockages, the mean total of lock delays for all vessels decreases by 3,588 hours, and the mean total time that locks are utilized decreases by 132 hours. For commercial tows, the mean total of lock delays decreases by 3,555.1 hours, the mean total time that tows utilize locks decreases by 133.3 hours, the mean number of simulated roundtrips completed annually increases by 5.3 to 1372.1, the mean time required to complete each roundtrip decreases annually by 2.6 hours from 525.9 hours to 523.3 hours, and the mean total amount of tow time needed to annually produce these roundtrips decreases by 749.8 hours. Table 27 presents an Analysis of Variance designed to explore the significance of the changes in the mean values of these and other selected variables. Table 27 reveals that the decrease in the roundtrip time per tow, the decrease in the total time per tow used to produce UMR system lockages, and the decrease in vessel wait times are significant at the 0.05 level while the changes in the other variables are not significant at the 0.05 level.

The implementation of the local SPF policy clearly alters the operation of the simulated system by significantly decreasing the expected level of lock delays faced by tows using the system. The decrease in lock delays averages approximately 9 percent and in turn decreases the mean time needed for tows to complete passage through the system by approximately 0.5 percent. However, due to the seasonality present in the model for when tows desire to utilize the simulated UMR system, the commercial tows respond to the improved operating conditions by (1) producing an average of approximately 0.4 percent additional annual roundtrips and by (2) exiting the system earlier on average than they otherwise would have and producing a small, but significant, decrease in the amount of time that each simulated tow uses the system. Stated differently, the seasonality of commercial tow demand for use of the system combined with the very small proportion of the total of their time available that tows engage in activities at these locks mutes the response of the simulated tows to the SPF policy. Consequently, if real tows operating on the UMR respond similarly to their simulated counterparts, there will likely only be a small response observable in the operations of the system to the reduced expected delays created by the implementation of the SPF policy.

7. CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

An event based, discrete simulation model has been presented and evaluated for use in investigating changes to the operational characteristics of the lower five 600 feet long lock chambers of the UMR navigation system. The UMR model extends earlier inland navigation simulation models of systems of locks by explicitly incorporating seasonal and interdependent traffic demands for specific origin and destination trips into the system simulation. Models that do not account for seasonal and interrelated traffic demands may not yield accurate representations of the operation of systems such as the UMR where seasonality is prevalent and important.

Analysis of Corps of Engineers OMNI data compiled from 2000 through 2003 indicates that these five locks do experience periodic traffic congestion, are subject to seasonal changes in demands for service, and do operate as a system in that they share a large amount of common interrelated commercial tow traffic. The simulation model is calibrated to this historic data and demonstrated to accurately portray the overall operation of the system and the periodic seasonality evident in the Corps OMNI data.

The UMR simulation model is employed to identify the potential impacts of the implementation of a SPF, shortest processing time first, lock queue tow dispatch policy to replace the existing FCFS, first come first served, tow policy for this segment of the UMR navigation system. The implementation of this SPF queue tow dispatch policy has a relatively small and subtle impact in the simulated UMR system when compared to the system operating with the existing queue tow dispatch policy. The SPF policy increases the expected operating efficiency of the simulated system by a small amount by reducing expected lock delays in the simulated system. The efficiency improvements consist of an increase in the total expected output of the system as measured by the expected annual tow roundtrips produced in the simulated system and a reduction in the expected amount of tow time needed to produce each simulated system roundtrip. However, the annual seasonality of tow demand for use of the system and the very small proportion of their total available productive time that tows engage in activities at these locks temper the total response of the simulated tows to the SPF policy. If tows operate on the real UMR navigation system respond in the same manner as their simulated counterparts, there will be only a small response in the real UMR system to the reduced delays and increased efficiencies created by the implementation of a SPF lock queue dispatch policy.

Other more extensive changes to the operating characteristics of the UMR navigation system may be readily examined using the framework of the UMR simulation model presented here. For example, the operational consequences of altering the performance characteristics of system infrastructure such as improving lock reliability can be readily examined in the framework adopted by the model by incorporating the new performance characteristics of the infrastructure into the simulation model and then evaluating the resulting changes in system performance.

Similarly, the addition of completely new infrastructure to the UMR navigation system such as replacing 600 feet long locks with larger 1200 feet long locks may be evaluated by including the performance characteristics of the new infrastructure in the framework adopted by the model and then identifying and evaluating the resulting changes in system performance. Using a simulation model that explicitly recognizes the seasonality of demand and the interdependence of lock operations to represent the operation of the UMR navigation system would be a distinct step forward over the techniques embedded in current Corps navigation system economic models used to evaluate this system.

The Corps currently uses two very different navigation system economic models, named the Tow Cost Model and the Essence Model, to evaluate new infrastructure proposed for the UMR system. The Tow Cost Model, which is itself a suite of models, typically employs an embedded simulation model to represent the operations of each lock in the system that simulates each individual lock's operating conditions in isolation while assuming independent traffic arrivals. Clearly, the Upper Mississippi River locks do not exhibit independent traffic arrivals and, consequently, the Tow Cost Model will not capture the interdependency effects of processing common and seasonal traffic.

The Essence Model utilizes a steady state approximation derived from queuing theory to describe the operation of each lock in the UMR navigation system. Again, the Upper Mississippi River locks do not exhibit independent traffic arrivals or operate as a steady state system and, consequently, the Essence Model will not capture the interdependency effects of processing common and seasonal traffic. A detailed description of the most recent application of both these models to evaluating infrastructure improvements in the UMR navigation system is presented in U.S. Army Corps of Engineers (2004), especially pages Econ 52-124.

Further, the framework of the UMR simulation model can be used to evaluate a range of alternatives that are not directly addressable in extant Corps of Engineers simulation and inland navigation system economic models. For example, the UMR simulation model could be used to evaluate the effects on system operations of a variable, time-sensitive fee designed to alter the seasonality of the tow demand for system use by providing an economic incentive to increase tow use during periods of typically low demand and decrease system use during periods of typically low demand.

The UMR simulation model presented here can be improved in at least two directions by further research. First, more explicit detail can be included in the model to represent the activities of tows at waterway locations other than these five UMR locks. Of course, this requires the availability of more detailed information regarding the actual operations of tows and vessels at locations other than these five UMR locks. The Corps OMNI lock database offers information regarding tow activities at other inland navigation system locks, but does not contain information on tow activities between appearances at system locks. The UMR simulation model can be extended using the OMNI data to explicitly incorporate larger segments of the inland navigation system and extending the geographic scope of the model scope will improve the representation of tow activities. However, detailed data regarding tow and barge operations at locations away from system locks is a critical need for improving the UMR system simulation model representation of the behavior of tows. By further partitioning the activities of tows into more, but related, activities of shorter duration the large amounts of time that tows operate away from system locks can be better understood and incorporated into the model.

Secondly, explicitly incorporating the relationship between the dynamics of the economics of tow operations and the seasonal demand exhibited by tow operators for UMR navigation system use into the simulation would add greatly to the utility of the simulation model. Abstracting from the macro-level, climate related operating restrictions evidenced in the system, tow operators can and do make economic choices electing to operate or not operate in the UMS system during different times of the year. In doing so, they superimpose their own economic seasonality onto the macro-level, climate related seasonality and create intra-seasonal dynamics in the operations of the system. Closing the feedback loop between the dynamic operating characteristics of the system and the dynamic seasonal demand exhibited by tow operators for use of the system will provide a complete analytical tool for use in evaluating the economic and operational consequences of any potential change to the operating characteristics of this segment of the inland navigation system.

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Figure 1. Map of the Upper Mississippi River (UMR) Navigation System
Source: U.S. Army Corps of Engineers

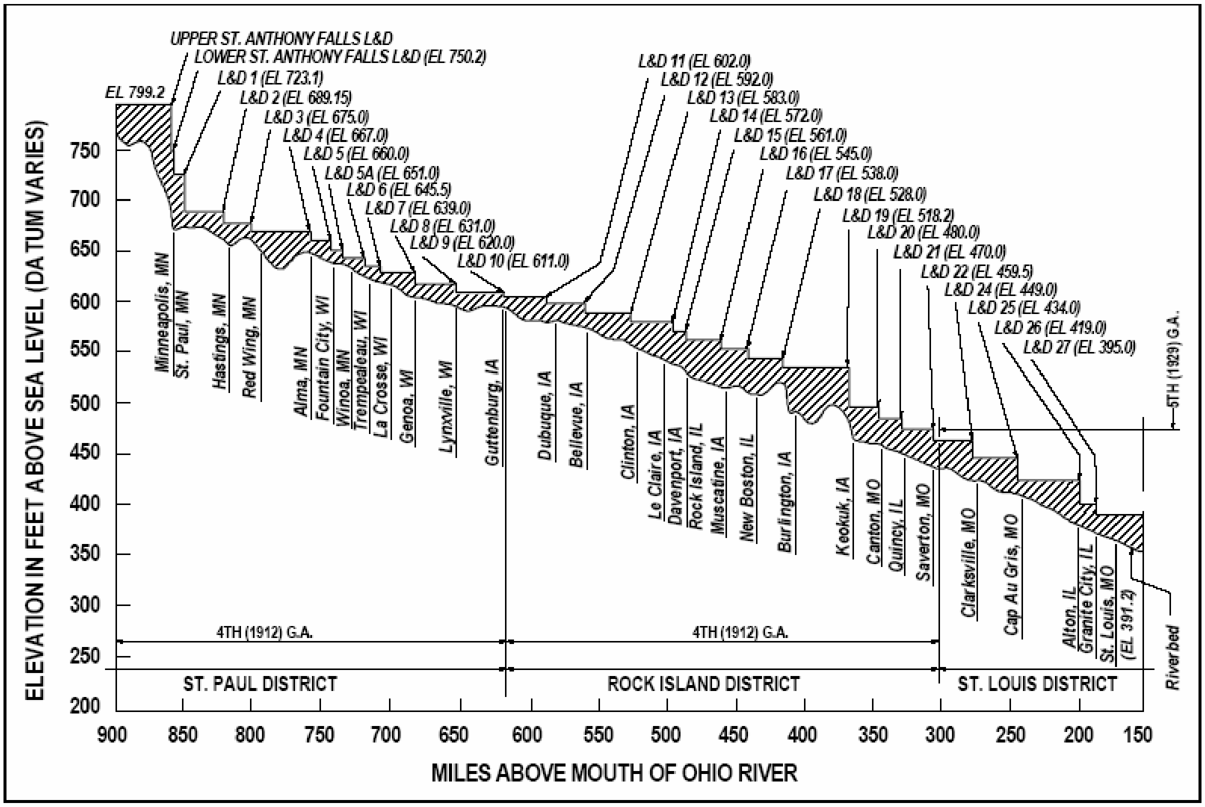

Figure 2. Schematic View of the Upper Mississippi River Pool System
Source: U.S. Army Corps of Engineers

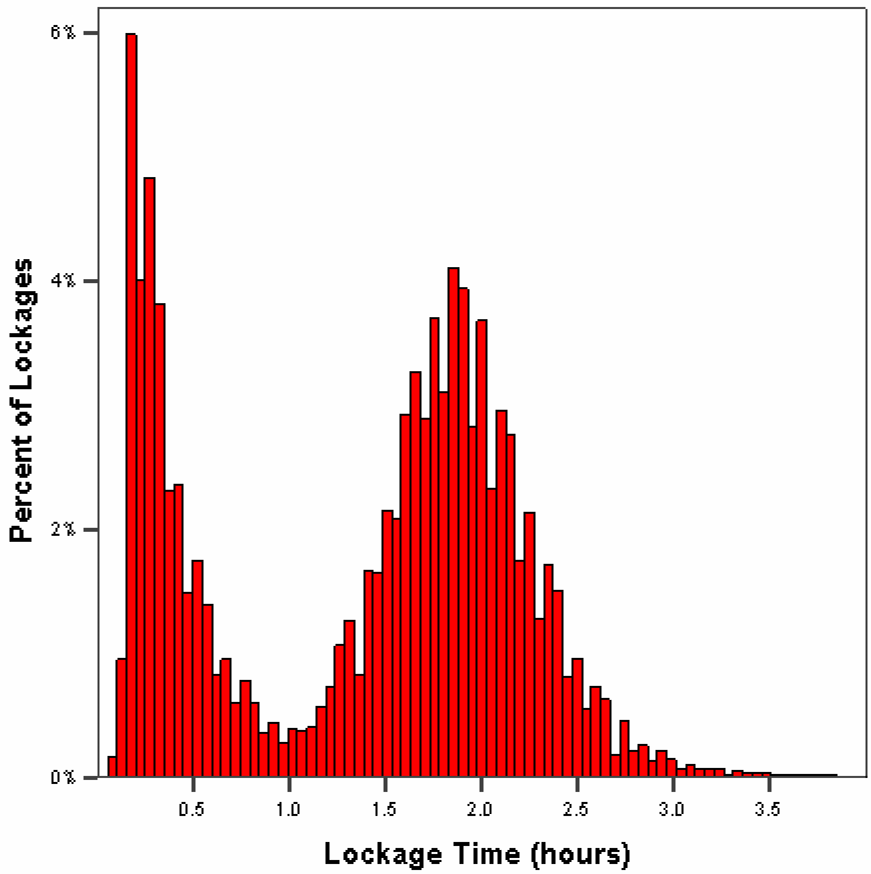

Figure 3. The Distribution of Lockage Times at Upper Mississippi River Locks 20 through 25, 2000 through 2003

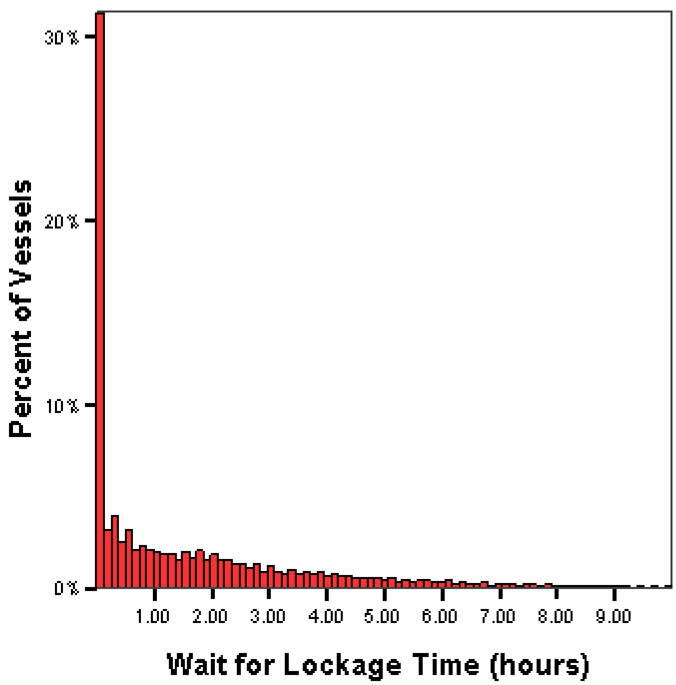

Figure 4. Panel A: The Distribution of Wait for Lockage Times, UMR Locks 20 through 25

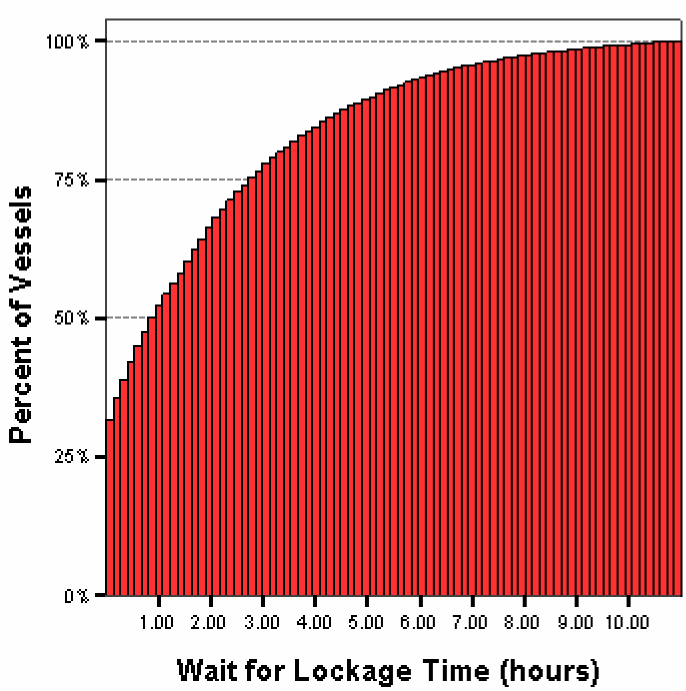

Figure 4. Panel B: The Cumulative Distribution of Wait Times, UMR Locks 20 through 25

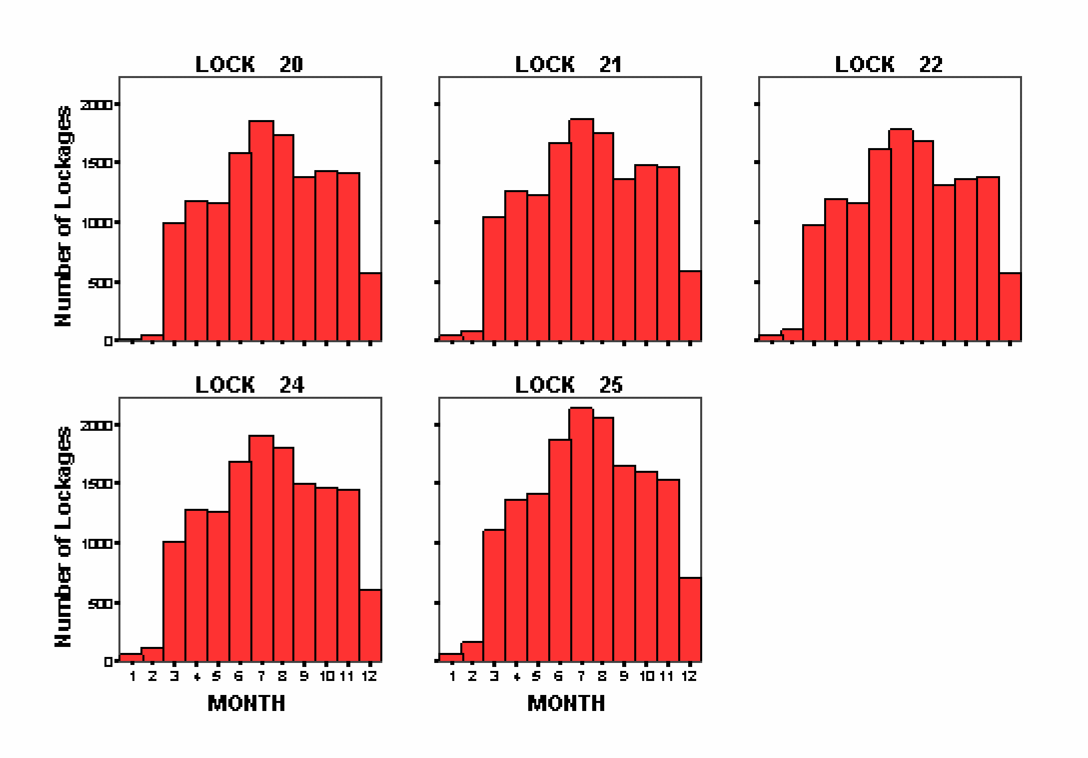

Figure 5. The Number of Lockages Completed at UMR Locks 20 through 25 by Month, 2000 through 2003

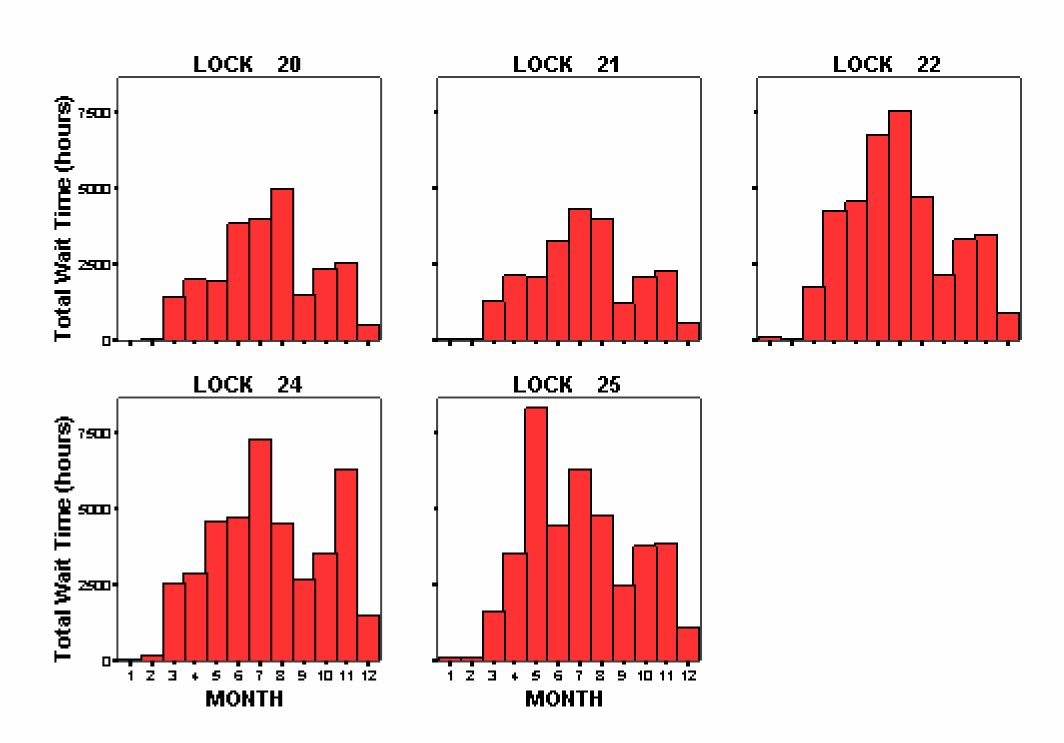

Figure 6. Aggregated Wait for Lockage Times for All Vessels by Lock and Month, 2000 through 2003

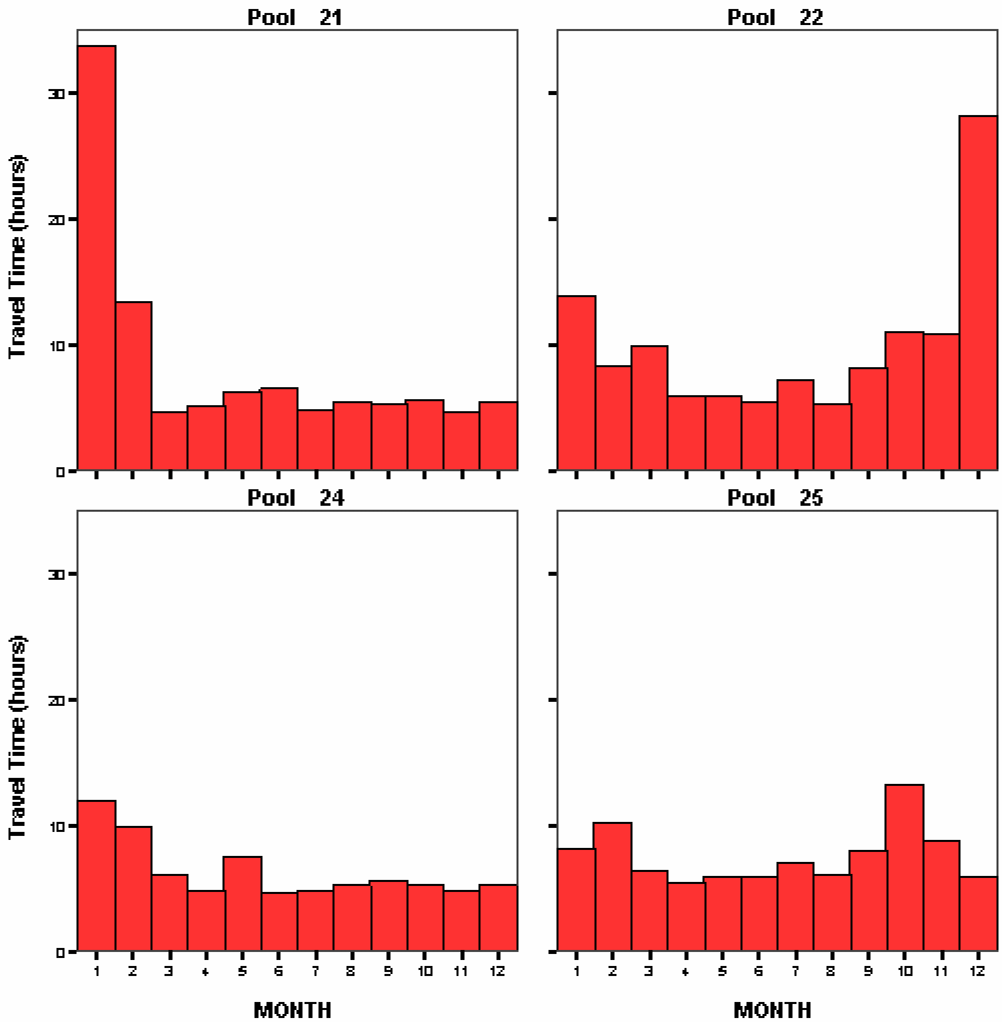

Figure 7. Mean Pool Transit Times for Commercial Tows by Month, 2000 through 2003

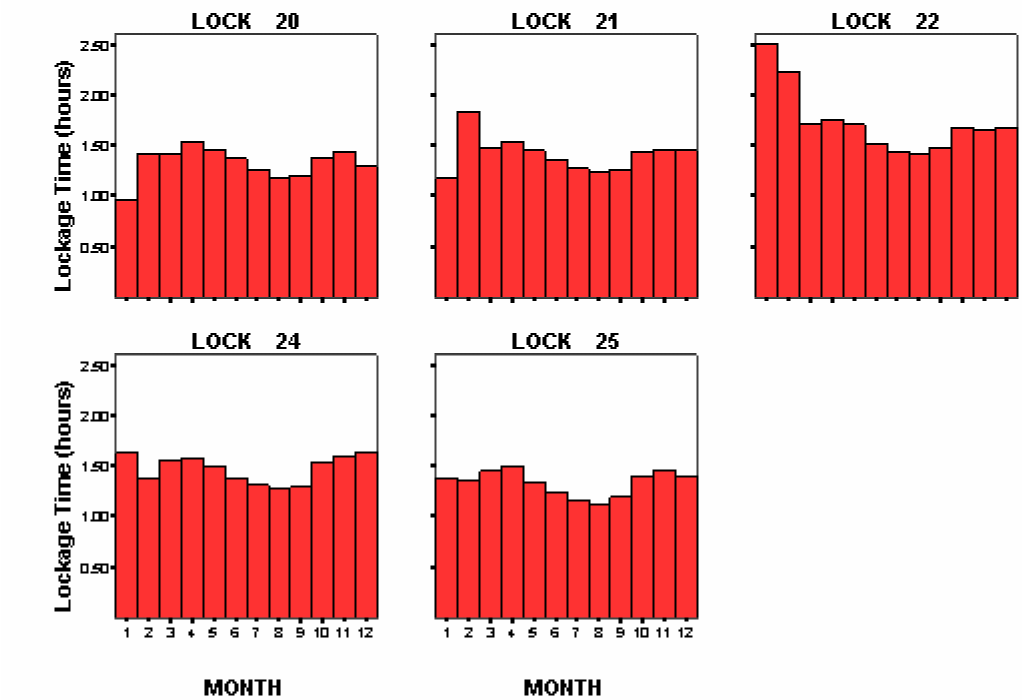

Figure 8. Mean Lockage Times for UMR Locks 20 through 25 by Month, 2000 through 2003

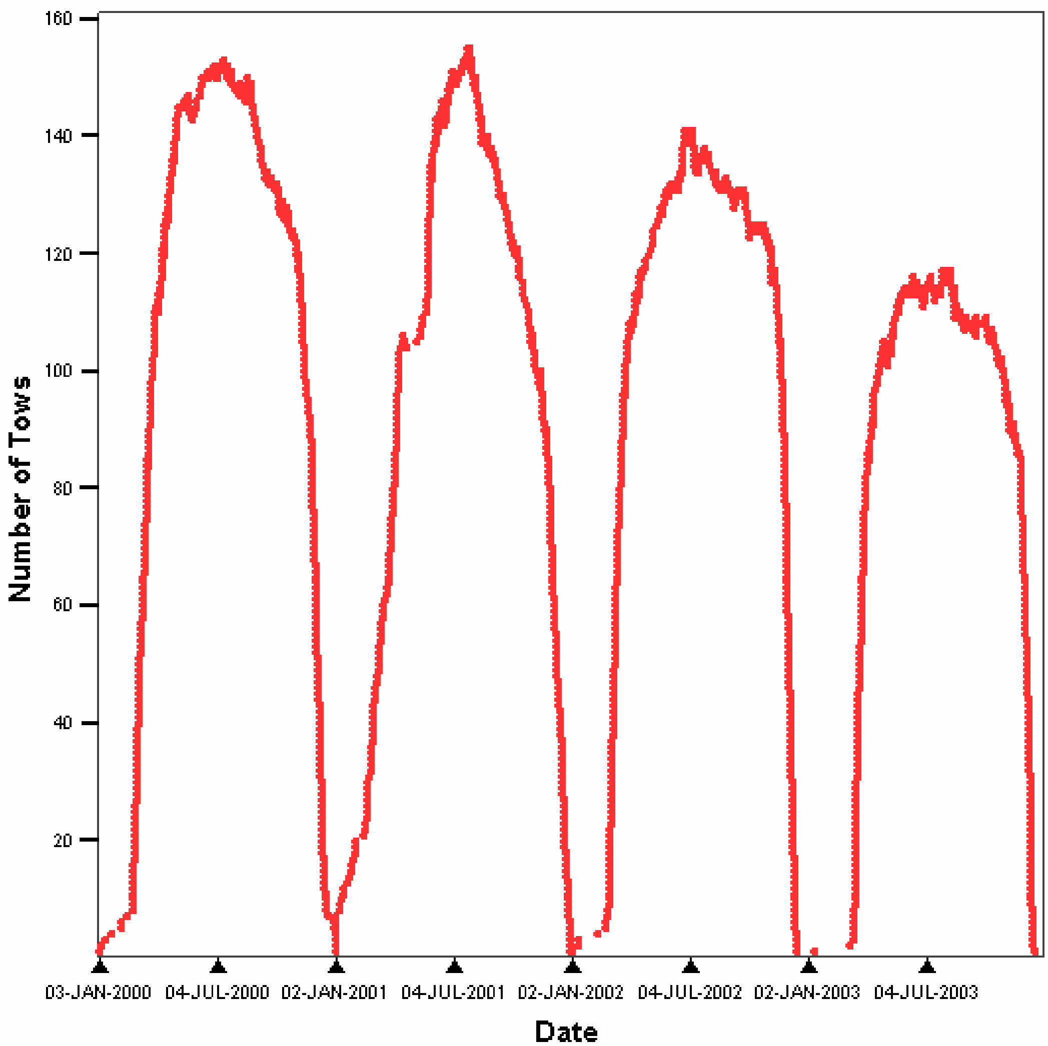

Figure 9. The Number of Tows That Have Produced at Least One Lockage in the System But Have Not Produced Their Final System Lockage, 2000 through 2003

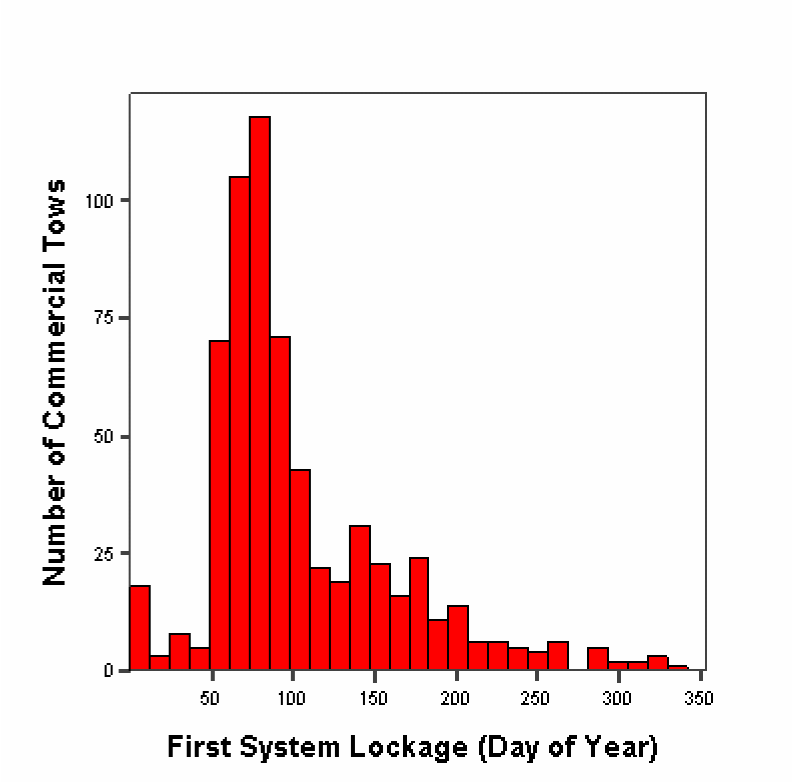

Figure 10. The Day of the Year of the First Lockage of Individual Commercial Tows at UMR Locks 20 through 25, 2000 through 2003

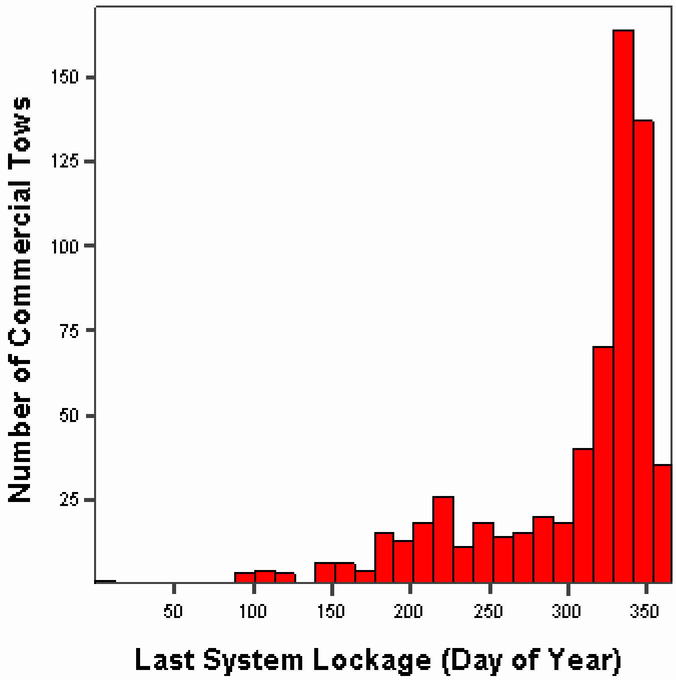

Figure 11. The Day of the Year of the Final System Lockage of individual Commercial Tows at UMR Locks 20 through 25, 2000 through 2003

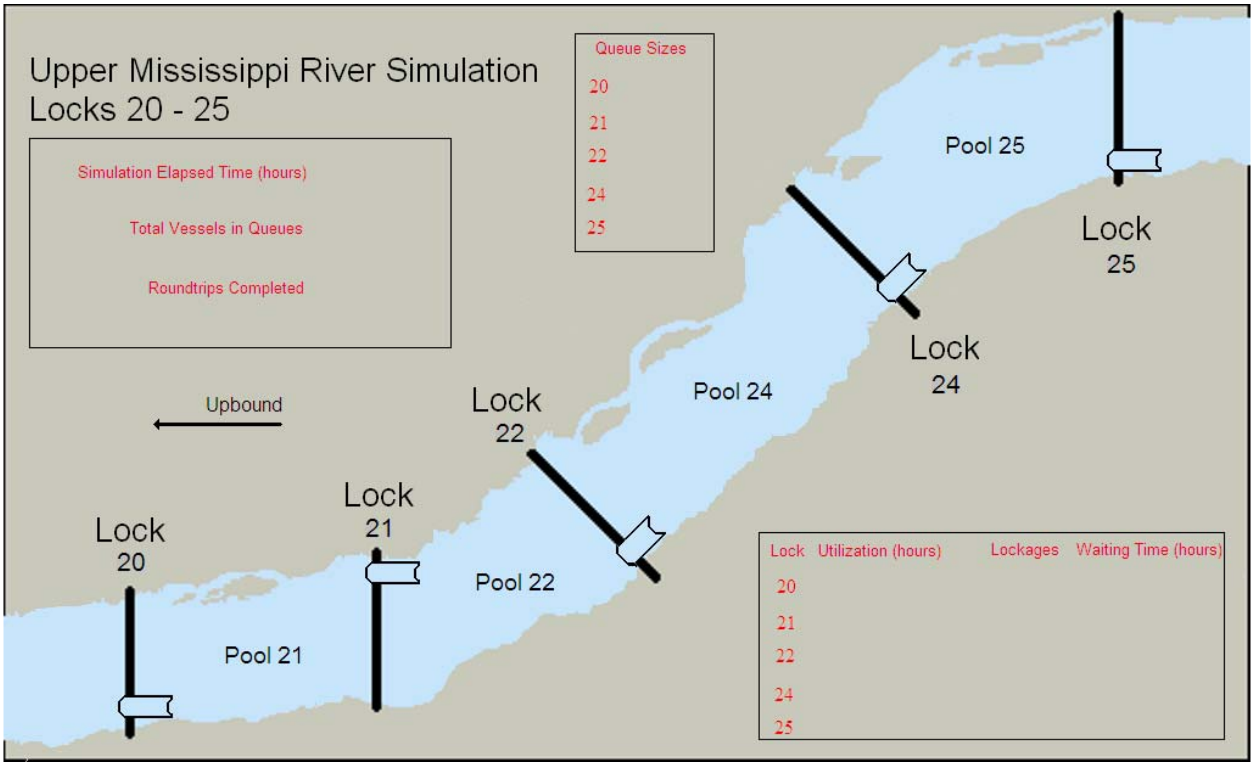

Figure 12. The Micro Saint 4.1 Screen Display Diagram for the UMR Simulation Model

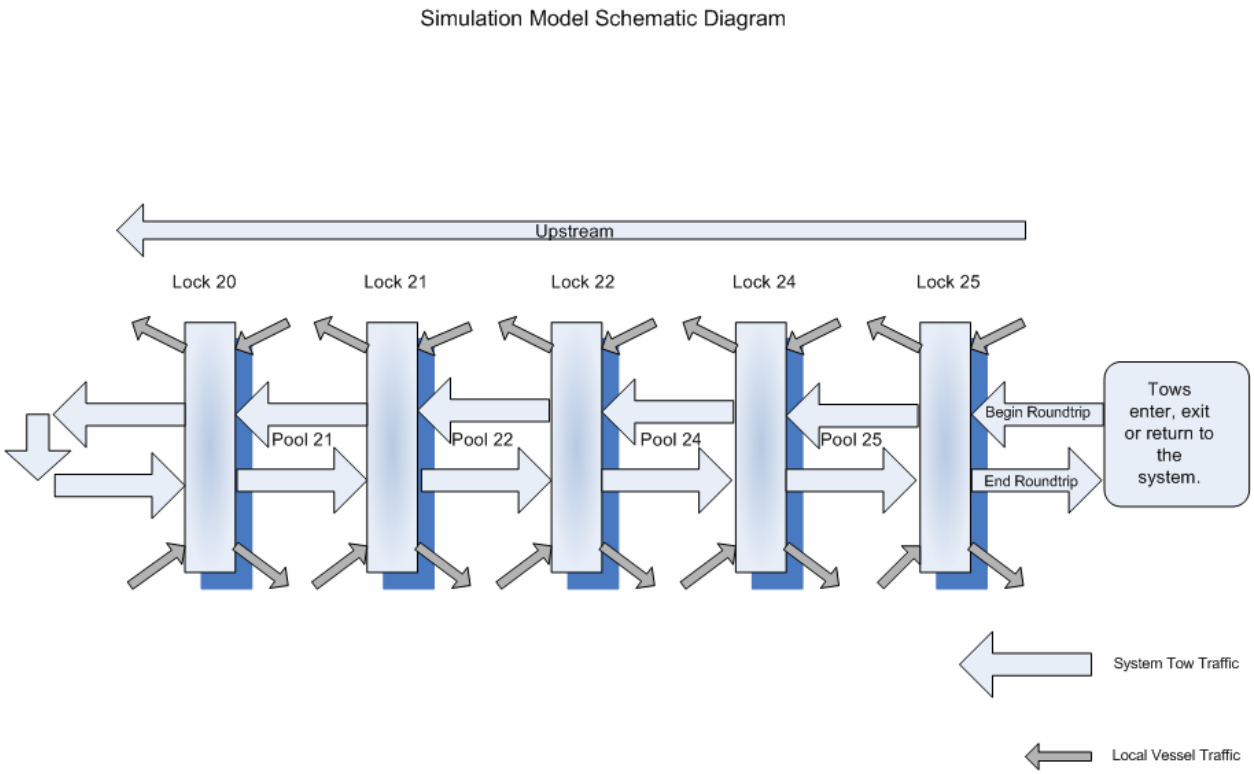

Figure 13. The UMR Simulation Model Schematic Diagram

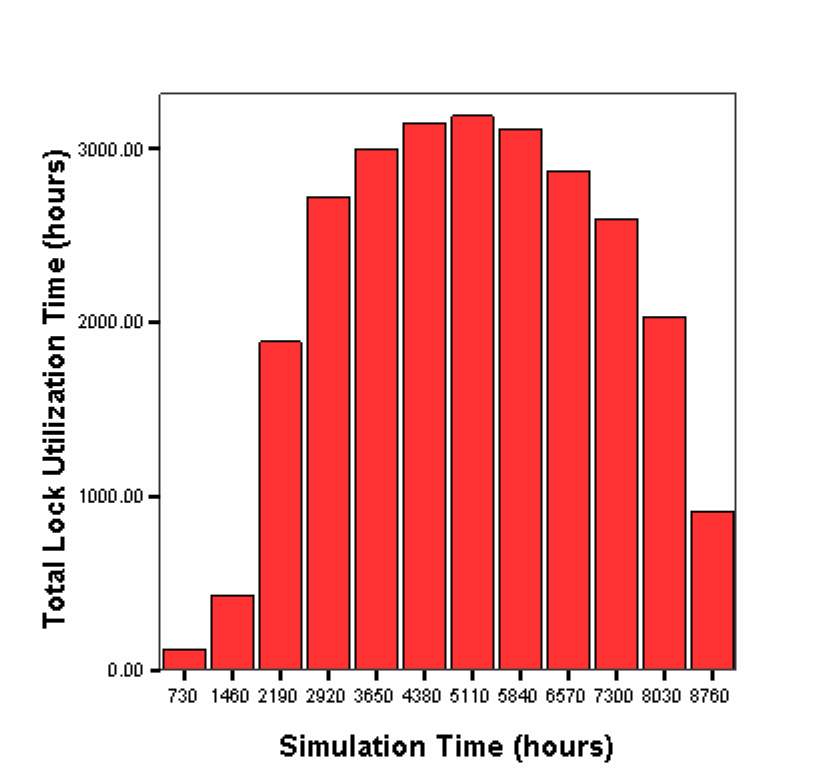

Figure 14. Mean Simulated Values of the Total Aggregated Lock Utilization Times for UMR Locks 20 through 25 for Twelve Equal Periods

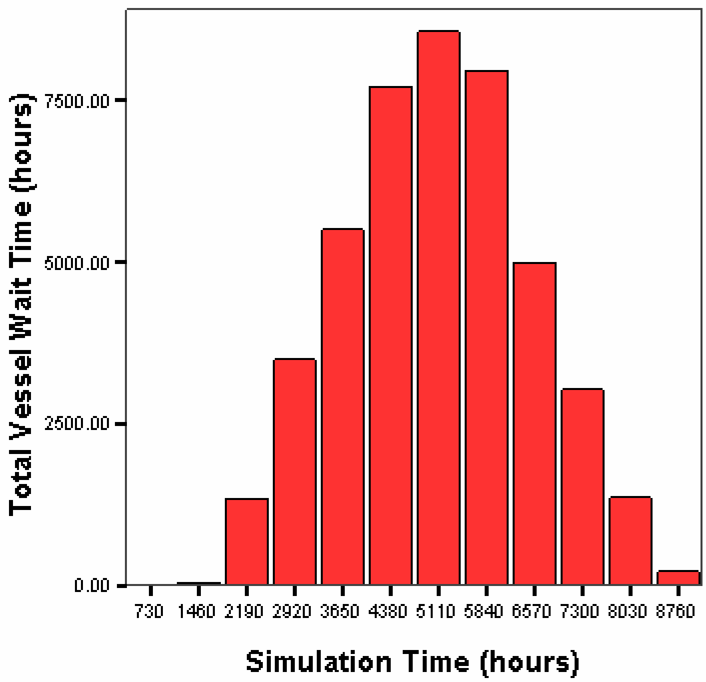

Figure 15. Mean Simulated Values of the Aggregated Total Lock Wait Times for UMR Locks 20 through 25 for Twelve Equal Periods

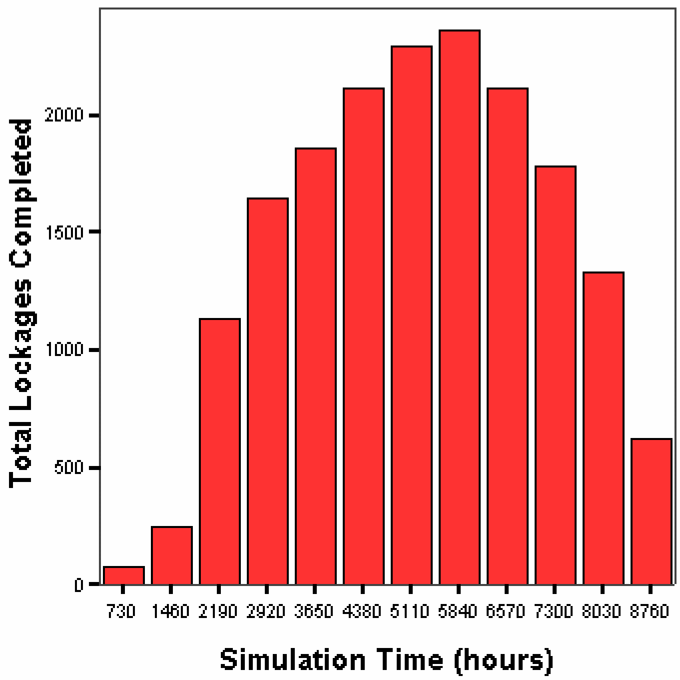

Figure 16. Mean Simulated Values of Total the Number of Lockages Completed at UMR Locks 20 through 25 for Twelve Equal Periods

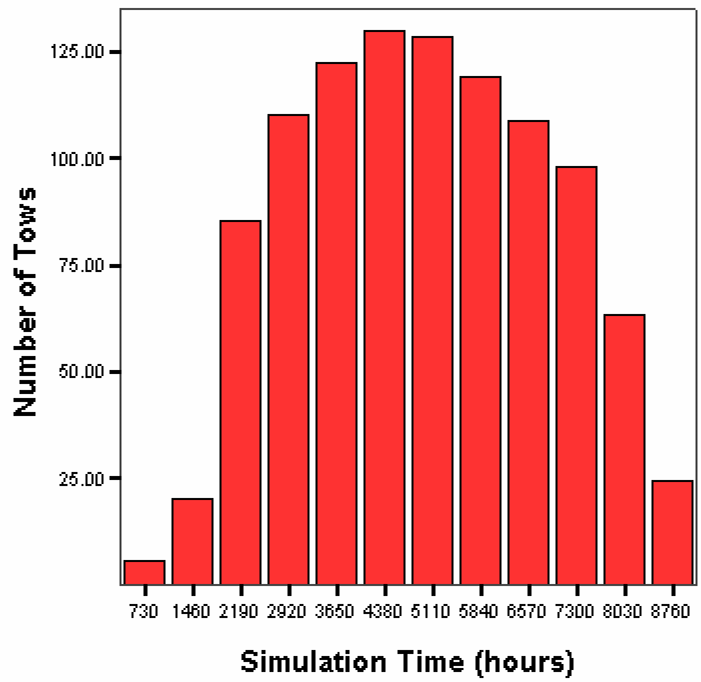

Figure 17. Mean Simulated Values of the Total Number of Tows Operating at UMR Locks 20 through 25 for Twelve Equal Periods

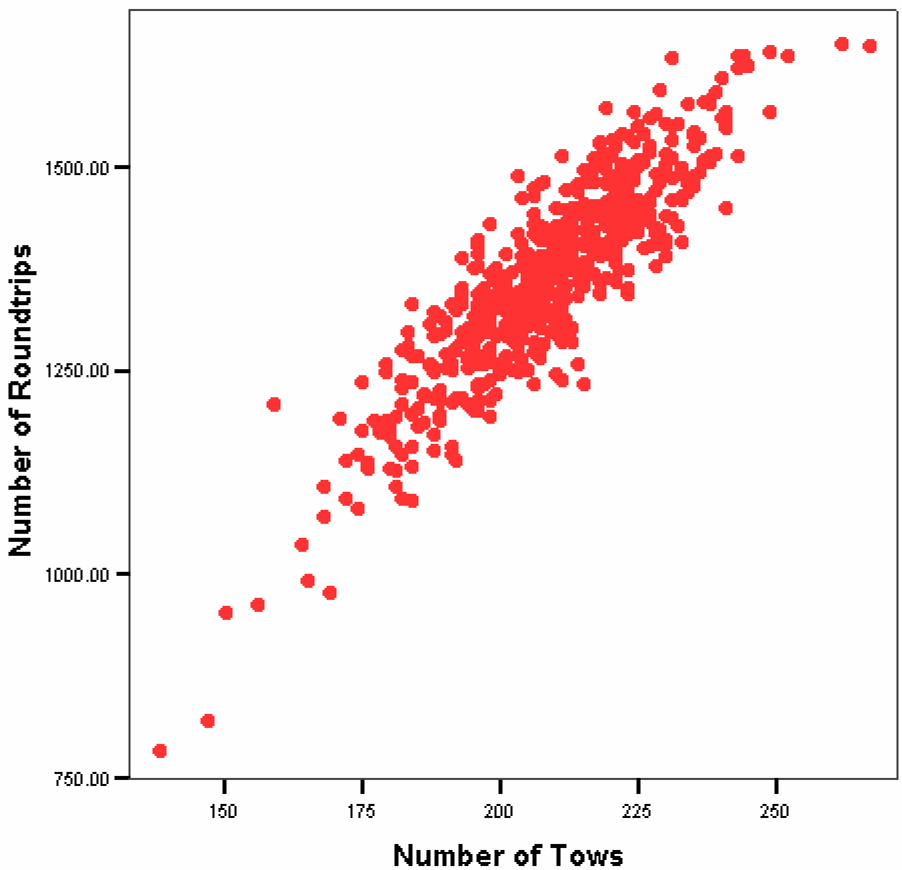

Figure 18. Roundtrips Completed and the Annual Number of Tows Operating in the System Compiled from 600 Runs of the UMR System Simulation Model

Lock	River Mile	Year Opened	Length (Feet)	Width (Feet)	Lift (Feet)	2002 Utilization (%)
Upper Mississippi River						
USA	853.9	1963	400	56	49	15
LSA	853.3	1959	400	56	25	16
1 (Main)	847.6	1930	400	56	38	17
1 (Auxiliary)	847.6	1932	400	56	38	0
2 (Main)	815.0	1930	500	110	12	36
2 (Auxiliary)	815.0	1948	600	110	12	n.a.
3	796.9	1938	600	110	8	39
4	752.8	1935	600	110	7	35
5	738.1	1935	600	110	9	32
5a	728.5	1936	600	110	5	33
6	714.0	1936	600	110	6	38
7	702.0	1937	600	110	8	40
8	679.0	1937	600	110	11	40
9	647.0	1938	600	110	9	41
10	615.0	1936	600	110	8	44
11	583.0	1937	600	110	11	51
12	556.0	1938	600	110	9	52
13	523.0	1938	600	110	11	50
14 (Main)	493.0	1939	600	110	11	69
14 (Auxiliary)	493.0	1922	320	80	11	7
15 (Main)	482.9	1934	600	110	16	71
15 (Auxiliary)	482.9	1934	360	110	16	14
16	457.2	1937	600	110	9	68
17	437.1	1939	600	110	8	74
18	410.5	1937	600	110	10	71
19	364.2	1957	1200	110	38	56
20	343.2	1936	600	110	10	73
21	324.9	1938	600	110	10	76
22	301.2	1938	600	110	10	82
24	273.4	1940	600	110	15	85
25	241.4	1939	600	110	15	80
Mel Price (26) (Main)	200.8	1990	1200	110	24	61
Mel Price (26) (Aux.)	200.8	1994	600	110	24	16
27 (Main)	185.5	1953	1200	110	21	68
27 (Auxiliary)	185.5	1953	600	110	21	14

Table 1. Selected Characteristics of the Locks in the UMR Navigation System
Source: U.S. Army Corps of Engineers

MONTH	YEAR	Mean (hours)	Lockages	Std. Deviation (hours)
January	2000	.0000	23	.00000
	2001	1.7481	166	4.67527
	2002	.0012	14	.00445
	2003	.0000	4	.00000
	Total	1.4019	207	4.24208
February	2000	1.0760	163	4.60158
	2001	.5648	296	1.27191
	2002	2.5018	19	7.14615
	2003	n/a	0	n/a
	Total	.8161	478	3.20848
March	2000	1.5144	1528	1.84527
	2001	.8234	1066	1.54950
	2002	2.4241	1535	4.85580
	2003	1.7369	1007	2.90295
	Total	1.6865	5136	3.24528
April	2000	3.0814	1873	3.63508
	2001	1.9867	1122	3.01575
	2002	2.0783	1701	2.49104
	2003	2.0323	1591	2.63217
	Total	2.3491	6287	3.03581
May	2000	2.2771	1985	2.53592
	2001	14.3627	744	26.04503
	2002	2.0113	1872	3.18279
	2003	1.4968	1618	1.92785
	Total	3.4399	6219	10.16991
June	2000	2.0439	2046	2.74431
	2001	3.6781	2291	3.89975
	2002	3.0839	2221	4.04113
	2003	1.8256	1880	2.40980
	Total	2.7127	8438	3.48092

Table 2. Mean and Standard Deviations of Wait for Lockage Times
UMR Locks 20 through 25, 2000 through 2003

MONTH	YEAR	Mean (hours)	Lockages	Std. Deviation (hours)
July	2000	1.8013	2434	2.22484
	2001	5.3820	2538	9.49168
	2002	2.8447	2418	3.66686
	2003	2.0228	2168	2.59354
	Total	3.0663	9558	5.67386
August	2000	3.5909	2275	10.91338
	2001	3.6355	2400	4.68905
	2002	1.4085	2242	1.90115
	2003	1.3341	2121	1.84267
	Total	2.5317	9038	6.22536
September	2000	1.5732	1942	2.58004
	2001	1.3466	1866	1.98650
	2002	1.2520	1859	1.93316
	2003	1.3572	1526	9.50882
	Total	1.3856	7193	4.79293
October	2000	2.8339	1885	3.74527
	2001	1.3628	1698	1.92396
	2002	2.2757	2025	2.89381
	2003	1.5882	1733	2.38506
	Total	2.0456	7341	2.90502
November	2000	2.3104	1837	2.87879
	2001	1.8075	1688	2.05200
	2002	3.8051	2135	4.46335
	2003	1.8766	1588	2.31000
	Total	2.5385	7248	3.28951
December	2000	1.7048	709	2.57404
	2001	1.0194	1016	1.73588
	2002	1.6265	587	3.61528
	2003	1.8039	725	2.18968
	Total	1.4840	3037	2.51609
Total	2000	2.3191	18700	4.69654
	2001	3.1955	16891	7.68257
	2002	2.3603	18628	3.50466
	2003	1.7018	15961	3.70364
	Total	2.4006	70180	5.16980

Table 2 (continued). Mean and Standard Deviations of Wait for Lockage Times UMR Locks 20 through 25, 2000 through 2003

EROC	A code indicating the Corps of Engineers District in which the lock is located.
RIVER_CODE*	A code that denotes the river in which the lock is located.
LOCK_NO*	The lock identification number assigned by the Corp of Engineers.
CHMBER_NO*	A code that describes which lock chamber (if the lock has multiple chambers) that the vessel used.
OPS_ID*	The Operation ID assigned for the transaction at the lock.
LOCKAGE_TYPE*	A code that denotes the lockage type. S (Single Cut), C (Multi-Cut), K (Knock Out), or V (Jack Knife)
VESSEL_NO*	The unique Coast Guard ID for the powered vessel completing the lockage.
FLOTILLA_NO*	A number assigned for tow at the each lock associated with the combination of tow and barges that comprise the fully assembled tow.
SOL_DATE*	The date and time that the lockage began.
ARRIVAL_DATE*	The date and time that the vessel arrived for lockage.
END_OF_LOCKAGE*	The date and time that the vessel completed its lockage.
END_OF_ENTRY	The date and time that the vessel completed its entry into the lock chamber.
START_OF_EXIT	The date and time that the vessel began its exit from the lock chamber.
NUM_OF_CMRCL_PSSNGRS	The number of commercial passengers in the vessel (if any).
ASST_CODE	A code that identifies if the vessel was assisted by another vessel during its lockage.

Table 3. OMNI Traffic Table Field Details

PVESSEL_NO	Relational field that corresponds with the VESSEL_ID field in the Traffic Table.
FLOTILLA_NO	Assigned for each vessel at each lock they transit.
EROC	A code for the Corps of Engineers District in which the lock is located.
FLOT_LENGTH	The length of the flotilla.
FLOT_WIDTH	The width of the flotilla.
FLOT_DRAFT_FT	The draft of the flotilla in measured to the next lowest foot.
FLOT_DRAFT_IN	The remainder of the draft of the flotilla measured in inches.
STOP_CODE	A code that indicates whether the vessel made a stop since its last lockage.
HAZARD_CODE	A code that indicates if there was hazardous cargo present in the flotilla.
NUM_LOADED_BRG	The number of loaded barges in the flotilla.
NUM_OF_EMPTY_BRG	The number of empty barges in the flotilla.
NEW_FLOTILLA_NO	A code that indicates if this is a new flotilla number assigned to a portion of a tow in lockage.

Table 4. OMNI Flotilla Table Field Details

VESSEL_NO*	The unique Coast Guard assigned vessel number for the towboat.
EROC	A code for the Corps of Engineers District in which the lock is located.
VESSEL_TYPE*	It can be T (Tow Boat), P (Commercial Passenger), G (Government Boat), or R (Recreational).
VESSEL_NAME	The registered name of the vessel.
VSL_FOREIGN_FLAG	An indicator to denote that the vessel has a foreign flag.
VESSEL_OWNER	The registered owner of the vessel.
VESSEL_HP*	The rated horsepower of the vessel.

Table 5. OMNI Vessel Table Field Details

EROC	A code for the Corps of Engineers District in which the lock is located.
RIVER_CODE	A code that denotes the river in which the lock is located. It can be MI, IL, or KS.
LOCK_NO*	The lock number assigned by Corp of Engineers.
CHMBER_NO	A code that describes which lock chamber (if the lock has multiple chambers) that the vessel used.
OPS_ID*	The Operation ID assigned for the transaction at the lock.
DIRECTION*	The direction of travel of the vessel. It can be up-bound or down-bound.
MULTI_VESSEL	Denotes if more than one powered vessel was included in the lockage.
NUM_LIGHT_BOATS	The number of light boats (towboats without barges) included in the lockage.
NUM_REC_BOATS	The number of recreation boats included in the lockage.

Table 6. OMNI Operations Table Field Details

LOCK	DIRECTION	LOCKAGE TYPE	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	Multi-Cut Tows	2.4532	4348	5.52669
		Other Vessels	.3914	1467	.69195
		Single Cut Tows	2.1103	972	4.13403
		Total	1.9585	6787	4.77557
	Upbound	Multi-Cut Tows	2.2695	4154	2.94849
		Other Vessels	.3719	1346	.73543
		Single Cut Tows	1.6520	1077	2.28302
		Total	1.7800	6577	2.64833
21	Downbound	Multi-Cut Tows	2.0103	4521	3.93470
		Other Vessels	.3846	1496	.74214
		Single Cut Tows	1.9340	1041	3.47683
		Total	1.6545	7058	3.49982
	Upbound	Multi-Cut Tows	2.1590	4286	4.73574
		Other Vessels	.4144	1389	1.18078
		Single Cut Tows	1.4742	1112	2.28900
		Total	1.6897	6787	3.97294
22	Downbound	Multi-Cut Tows	3.4378	4536	3.94979
		Other Vessels	.4992	1248	.78973
		Single Cut Tows	3.2518	911	3.99801
		Total	2.8647	6695	3.76090
	Upbound	Multi-Cut Tows	3.8981	4319	4.92952
		Other Vessels	.6188	1194	2.21051
		Single Cut Tows	2.7865	970	3.55039
		Total	3.1278	6483	4.53251
24	Downbound	Multi-Cut Tows	3.6429	4705	4.43292
		Other Vessels	.1852	1573	.61891
		Single Cut Tows	2.6085	904	3.24123
		Total	2.7554	7182	4.03028
	Upbound	Multi-Cut Tows	3.9758	4451	8.36997
		Other Vessels	.4590	1529	6.22727
		Single Cut Tows	2.4463	987	3.87461
		Total	2.9873	6967	7.57980
25	Downbound	Multi-Cut Tows	3.0437	4726	3.99339
		Other Vessels	.3526	1963	.76148
		Single Cut Tows	2.5486	972	3.55220
		Total	2.2913	7661	3.59245
	Upbound	Multi-Cut Tows	4.3418	4466	11.32155
		Other Vessels	.3475	2443	1.18171
		Single Cut Tows	2.3049	1074	3.77842
		Total	2.8454	7983	8.78912

Table 7. Selected Summary Statistics of Wait for Lockage Time Distributions by Lock, Direction, and Lockage Type, 2000 through 2003

LOCK	DIRECTION	LOCKAGE TYPE	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	Multi-Cut Tows	1.8927	4348	.61299
		Other Vessels	.2842	1467	.30125
		Single Cut Tows	.6600	972	.50924
		Total	1.3685	6787	.89415
	Upbound	Multi-Cut Tows	1.8103	4154	.50341
		Other Vessels	.3182	1346	.43748
		Single Cut Tows	.6509	1077	.52943
		Total	1.3151	6577	.82197
21	Downbound	Multi-Cut Tows	1.9890	4521	.48484
		Other Vessels	.2770	1496	.21985
		Single Cut Tows	.6332	1041	.38999
		Total	1.4261	7058	.87110
	Upbound	Multi-Cut Tows	1.8370	4286	.52721
		Other Vessels	.2962	1389	.25147
		Single Cut Tows	.6615	1112	.41052
		Total	1.3290	6787	.81875
22	Downbound	Multi-Cut Tows	2.1626	4536	.66184
		Other Vessels	.3463	1248	.39730
		Single Cut Tows	.8654	911	1.32088
		Total	1.6475	6695	1.06866
	Upbound	Multi-Cut Tows	2.0118	4319	.61214
		Other Vessels	.3527	1194	.49750
		Single Cut Tows	.8220	970	.71348
		Total	1.5282	6483	.92535
24	Downbound	Multi-Cut Tows	2.1010	4705	.62686
		Other Vessels	.3148	1573	.25158
		Single Cut Tows	.7372	904	.74718
		Total	1.5381	7182	.97858
	Upbound	Multi-Cut Tows	1.8178	4451	.46306
		Other Vessels	.3300	1529	.20358
		Single Cut Tows	.7060	987	.42623
		Total	1.3338	6967	.77359
25	Downbound	Multi-Cut Tows	2.0264	4726	.64782
		Other Vessels	.2723	1963	.21992
		Single Cut Tows	.6533	972	.46279
		Total	1.4027	7661	.96804
	Upbound	Multi-Cut Tows	1.8271	4466	.60917
		Other Vessels	.2879	2443	.20116
		Single Cut Tows	.6642	1074	.59361
		Total	1.1996	7983	.88352

Table 8. Selected Summary Statistics of Lockage Time Distributions by Lock, Direction, and Lockage Type, 2000 through 2003

Destination Lock	Destination Direction	Previous Lock	Previous Direction	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	20	Upbound	251.8339	4256	295.72261
	Upbound	20	Downbound	8.2996	42	5.90629
	Upbound	21	Upbound	4.3880	4097	4.96654
21	Downbound	20	Downbound	3.2458	4381	4.72841
	Downbound	21	Upbound	14.7897	126	50.95451
	Upbound	21	Downbound	9.4990	69	5.27156
	Upbound	22	Upbound	4.8132	4193	2.75780
22	Downbound	21	Downbound	3.2953	4438	2.33310
	Downbound	22	Upbound	8.7925	67	9.60362
	Upbound	22	Downbound	13.3422	66	12.41240
	Upbound	24	Upbound	6.1937	4219	10.43918
24	Downbound	22	Downbound	4.6320	4502	3.25270
	Downbound	24	Upbound	15.5079	164	25.63340
	Upbound	24	Downbound	10.1424	90	6.06978
	Upbound	25	Upbound	7.1328	4327	3.52727
25	Downbound	24	Downbound	4.4184	4579	1.68673
	Downbound	25	Upbound	13.3986	109	18.40783
	Upbound	25	Downbound	220.4298	3835	422.16461

Table 9. Selected Summary Statistics of Transit Times between Locks for Multi-Cut Tows, 2000 through 2003

Destination Lock	Destination Direction	Previous Lock	Previous Direction	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	20	Upbound	188.9343	902	459.64520
	Upbound	20	Downbound	60.1800	137	266.92060
	Upbound	21	Upbound	5.9442	856	28.64324
21	Downbound	20	Downbound	9.4736	720	79.80730
	Downbound	21	Upbound	135.8546	265	224.44535
	Upbound	21	Downbound	16.7584	392	40.14640
	Upbound	22	Upbound	14.6179	675	105.31233
22	Downbound	21	Downbound	11.4209	584	76.88729
	Downbound	22	Upbound	23.0637	306	82.18753
	Upbound	22	Downbound	113.3339	56	283.37568
	Upbound	24	Upbound	5.9691	902	17.09712
24	Downbound	22	Downbound	5.7052	778	25.39592
	Downbound	24	Upbound	78.5335	112	199.48811
	Upbound	24	Downbound	28.7156	47	56.94318
	Upbound	25	Upbound	6.8154	927	24.69163
25	Downbound	24	Downbound	8.9213	852	114.69242
	Downbound	25	Upbound	68.6983	105	137.96422
	Upbound	25	Downbound	384.4348	823	798.30050

Table 10. Selected Summary Statistics of Travel Times between Locks for Single Cut Tows, 2000 through 2003

Lock	Direction	Lockage Type	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	Exchange	1.89	1661	.743
		Fly	1.99	1253	.565
		Turnback	1.81	1434	.455
		Total	1.89	4348	.613
	Upbound	Exchange	1.94	1564	.412
		Fly	1.91	1168	.601
		Turnback	1.59	1422	.427
		Total	1.81	4154	.503
21	Downbound	Exchange	1.93	1737	.475
		Fly	2.25	1308	.419
		Turnback	1.83	1476	.458
		Total	1.99	4521	.485
	Upbound	Exchange	1.93	1721	.405
		Fly	2.01	1171	.609
		Turnback	1.57	1394	.485
		Total	1.84	4286	.527
22	Downbound	Exchange	2.13	1857	.546
		Fly	2.52	964	.868
		Turnback	1.99	1715	.559
		Total	2.16	4536	.662
	Upbound	Exchange	2.13	1770	.511
		Fly	2.28	792	.618
		Turnback	1.77	1757	.620
		Total	2.01	4319	.612
24	Downbound	Exchange	2.17	1812	.619
		Fly	2.18	935	.696
		Turnback	2.00	1958	.586
		Total	2.10	4705	.627
	Upbound	Exchange	1.91	1762	.508
		Fly	1.94	875	.400
		Turnback	1.67	1814	.403
		Total	1.82	4451	.463
25	Downbound	Exchange	2.03	2311	.471
		Fly	2.34	719	.694
		Turnback	1.89	1696	.778
		Total	2.03	4726	.648
	Upbound	Exchange	1.94	1778	.590
		Fly	2.04	852	.760
		Turnback	1.62	1836	.470
		Total	1.83	4466	.609

Table 11. Selected Summary Statistics of Lockage Time Distributions for Multi-Cut Tows, 2000 through 2003

Lock	Direction	Lockage Type	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	Exchange	.68	320	.405
		Fly	.73	286	.723
		Turnback	.59	366	.360
		Total	.66	972	.509
	Upbound	Exchange	.68	381	.427
		Fly	.71	347	.726
		Turnback	.57	349	.364
		Total	.65	1077	.529
21	Downbound	Exchange	.61	347	.390
		Fly	.76	301	.441
		Turnback	.55	393	.318
		Total	.63	1041	.390
	Upbound	Exchange	.69	405	.459
		Fly	.78	327	.403
		Turnback	.53	380	.318
		Total	.66	1112	.411
22	Downbound	Exchange	.82	335	.826
		Fly	1.16	204	2.223
		Turnback	.75	372	.947
		Total	.87	911	1.321
	Upbound	Exchange	.82	409	.673
		Fly	1.01	221	.996
		Turnback	.70	340	.480
		Total	.82	970	.713
24	Downbound	Exchange	.72	345	.702
		Fly	.72	213	.300
		Turnback	.76	346	.955
		Total	.74	904	.747
	Upbound	Exchange	.70	398	.464
		Fly	.79	223	.418
		Turnback	.66	366	.379
		Total	.71	987	.426
25	Downbound	Exchange	.72	334	.520
		Fly	.69	233	.367
		Turnback	.58	405	.453
		Total	.65	972	.463
	Upbound	Exchange	.69	419	.516
		Fly	.71	279	.674
		Turnback	.61	376	.607
		Total	.66	1074	.594

Table 12. Selected Summary Statistics of Lockage Time Distributions for Single Cut Tows, 2000 through 2003

Lock	Direction	Lockage Type	Mean (hours)	Number	Std. Deviation (hours)
20	Downbound	Exchange	.29	511	.465
		Fly	.29	619	.138
		Turnback	.26	337	.176
		Total	.28	1467	.301
	Upbound	Exchange	.32	524	.644
		Fly	.34	566	.221
		Turnback	.26	256	.219
		Total	.32	1346	.437
21	Downbound	Exchange	.26	529	.188
		Fly	.30	609	.233
		Turnback	.26	358	.236
		Total	.28	1496	.220
	Upbound	Exchange	.27	547	.230
		Fly	.33	579	.273
		Turnback	.28	263	.235
		Total	.30	1389	.251
22	Downbound	Exchange	.29	527	.281
		Fly	.46	336	.610
		Turnback	.32	385	.256
		Total	.35	1248	.397
	Upbound	Exchange	.30	564	.246
		Fly	.48	325	.856
		Turnback	.31	305	.234
		Total	.35	1194	.498
24	Downbound	Exchange	.45	173	.396
		Fly	.29	1283	.210
		Turnback	.39	117	.314
		Total	.31	1573	.252
	Upbound	Exchange	.42	253	.237
		Fly	.31	1150	.187
		Turnback	.37	126	.219
		Total	.33	1529	.204
25	Downbound	Exchange	.28	528	.210
		Fly	.27	1145	.199
		Turnback	.28	290	.301
		Total	.27	1963	.220
	Upbound	Exchange	.27	682	.166
		Fly	.29	1389	.179
		Turnback	.29	372	.310
		Total	.29	2443	.201

Table 13. Selected Summary Statistics of Lockage Time Distributions for Local Lockages, 2000 through 2003

DIRECTION			LOCK 20	21	22	24	25	Total
Downbound	Month	1	0.3	1.8	0.8	1.3	1.5	5.5
		2	2.5	2.0	2.5	2.5	4.0	13.5
		3	23.8	21.5	16.5	19.8	23.0	104.5
		4	15.3	19.0	14.8	21.0	21.0	91.0
		5	13.8	19.3	13.3	20.8	27.5	94.5
		6	30.3	42.0	33.5	38.3	53.0	197.0
		7	62.0	62.8	52.0	63.5	83.5	323.8
		8	74.0	74.3	64.5	71.0	95.8	379.5
		9	60.0	54.8	49.0	72.3	85.8	321.8
		10	53.3	53.0	45.0	53.8	62.8	267.8
		11	18.8	17.8	14.3	21.5	24.0	96.3
		12	13.0	6.0	6.0	7.8	9.0	41.8
	Total		366.8	374.0	312.0	393.3	490.8	1,936.8
Upbound	Month	1	0.3	1.5	1.5	1.5	1.3	6.0
		2	2.5	1.5	0.5	1.0	3.3	8.8
		3	16.3	12.8	7.8	11.0	28.5	76.3
		4	11.3	14.3	10.3	17.3	35.5	88.5
		5	21.8	25.0	19.5	26.0	52.0	144.3
		6	36.8	41.8	37.8	48.5	77.5	242.3
		7	57.8	58.3	50.5	63.5	91.8	321.8
		8	63.3	66.0	60.8	79.5	115.0	384.5
		9	44.0	47.0	44.5	54.0	81.3	270.8
		10	26.0	25.3	18.3	28.5	44.3	142.3
		11	31.0	32.8	29.5	33.8	48.8	175.8
		12	25.8	21.3	17.8	17.8	31.8	114.3
	Total		336.5	347.3	298.5	382.3	610.8	1,975.3

Table 14. Mean Number of Local Vessel Arrivals by Direction of Travel and Month of Arrival UMR Locks 20 through 25, 2000 through 2003

DIRECTION			LOCK 20	21	22	24	25
Downbound	Month	1	2,976.0	425.1	992.0	595.2	496.0
		2	268.8	336.0	268.8	268.8	168.0
		3	31.3	34.6	45.1	37.7	32.3
		4	47.2	37.9	48.8	34.3	34.3
		5	54.1	38.6	56.2	35.9	27.1
		6	23.8	17.1	21.5	18.8	13.6
		7	12.0	11.9	14.3	11.7	8.9
		8	10.1	10.0	11.5	10.5	7.8
		9	12.0	13.2	14.7	10.0	8.4
		10	14.0	14.0	16.5	13.8	11.9
		11	38.4	40.6	50.5	33.5	30.0
		12	57.2	124.0	124.0	96.0	82.7
Upbound	Month	1	2,976.0	496.0	496.0	496.0	595.2
		2	268.8	448.0	1,344.0	672.0	206.8
		3	45.8	58.4	96.0	67.6	26.1
		4	64.0	50.5	70.2	41.7	20.3
		5	34.2	29.8	38.2	28.6	14.3
		6	19.6	17.2	19.1	14.8	9.3
		7	12.9	12.8	14.7	11.7	8.1
		8	11.8	11.3	12.2	9.4	6.5
		9	16.4	15.3	16.2	13.3	8.9
		10	28.6	29.5	40.8	26.1	16.8
		11	23.2	22.0	24.4	21.3	14.8
		12	28.9	35.0	41.9	41.9	23.4

Table 15. Mean Hours between Local Vessel Arrivals by Direction of Travel and Month, 2000 through 2003

	Mean Hours Between Arrivals	
Month	*Small Tows*	*Large Tows*
1	496.00	186.00
2	179.20	52.71
3	45.78	11.63
4	72.00	29.09
5	135.27	41.92
6	115.20	52.36
7	148.80	85.03
8	110.22	330.67
9	144.00	261.82
10	119.04	372.00
11	205.71	192.00
12	270.55	744.00
Total	120.83	55.62

Table 16. Mean Hours between Arrivals of New System Tows, 2000 through 2003

Tow Type				Downbound Lockages at Lock 25 Tow Returned	Tow Did Not Return	Total
Multi-Cut Tows	Month	1	Number	11	0	11
			% within Month	100.0%	0.0%	100.0%
		2	Number	18	0	18
			% within Month	100.0%	0.0%	100.0%
		3	Number	230	6	236
			% within Month	97.5%	2.5%	100.0%
		4	Number	433	13	446
			% within Month	97.1%	2.9%	100.0%
		5	Number	396	20	416
			% within Month	95.2%	4.8%	100.0%
		6	Number	530	25	555
			% within Month	95.5%	4.5%	100.0%
		7	Number	558	41	599
			% within Month	93.2%	6.8%	100.0%
		8	Number	456	54	510
			% within Month	89.4%	10.6%	100.0%
		9	Number	343	33	376
			% within Month	91.2%	8.8%	100.0%
		10	Number	385	35	420
			% within Month	91.7%	8.3%	100.0%
		11	Number	341	154	495
			% within Month	68.9%	31.1%	100.0%
		12	Number	64	208	272
			% within Month	23.5%	76.5%	100.0%
	Total		Number	3,765	589	4,354
			% within Year	86.5%	13.5%	100.0%

Table 17. Probabilities by Month that a Multi-cut Tow Returns to the System after Exiting Lock 25 Downbound, 2000 through 2003

Single Cut Tows	Month	1	Number	11	2	13
			% within Month	84.6%	15.4%	100.0%
		2	Number	20	0	20
			% within Month	100.0%	0.0%	100.0%
		3	Number	62	6	68
			% within Month	91.2%	8.8%	100.0%
		4	Number	65	15	80
			% within Month	81.3%	18.8%	100.0%
		5	Number	53	6	59
			% within Month	89.8%	10.2%	100.0%
		6	Number	58	14	72
			% within Month	80.6%	19.4%	100.0%
		7	Number	60	13	73
			% within Month	82.2%	17.8%	100.0%
		8	Number	69	11	80
			% within Month	86.3%	13.8%	100.0%
		9	Number	63	24	87
			% within Month	72.4%	27.6%	100.0%
		10	Number	54	30	84
			% within Month	64.3%	35.7%	100.0%
		11	Number	45	57	102
			% within Month	44.1%	55.9%	100.0%
		12	Number	21	37	58
			% within Month	36.2%	63.8%	100.0%
	Total		Number	581	215	796
			% within Year	73.0%	27.0%	100.0%

Table 17 (continued). Probabilities by Month that a Single Cut Tow Returns to the System after Exiting Lock 25 Downbound, 2000 through 2003

Micro Saint Variable Name	Use or Purpose
a	Chamber Turnback Time Needed for a Turnback Lockage
boats_20	Count of Number of Tows North of Lock 20
boats_26	Count of Number of Tows South of Lock 25
clock	Micro Saint 4.1 System Variable
downbound *	Indicates Each Vessel's Direction of Travel (Downbound=1)
duration	Micros Saint 4.1 System Variable
large_system_tow_time	Accumulated Time Spent by Large Tows in the System
large_tow_exit_prob*	Probability that a Large Tow does not Return to the System
large_tow_start_adj	Alters the Mean Inter-arrival Times for Large Tows
large_tow_start_rate*	Mean Time Between Initial Lockages of Large Tows
large_tows	Number of Large Tow Tags to be Created
large_tows_created	Running Count of the Number of Large Tow Tags Created
large_tows_released	Number of Large Tows that Entered the System
last_dir*	Direction of Last Lockage at Each Lock (Downbound=1)
local_interarrival_time*	Mean Inter-arrival Times for Local Lock Traffic
local20	Count of Local Lockages Completed at Lock 20
local21	Count of Local Lockages Completed at Lock 21
local22	Count of Local Lockages Completed at Lock 22
local24	Count of Local Lockages Completed at Lock 24
local25	Count of Local Lockages Completed at Lock 25
lock_time20*	Means of Lockage Time Distributions Lock 20
lock_time21*	Means of Lockage Time Distributions Lock 21
lock_time22*	Means of Lockage Time Distributions Lock 22
lock_time24*	Means of Lockage Time Distributions Lock 24
lock_time25*	Means of Lockage Time Distributions Lock 25
lock_util*	Total Utilization Time of Each Lock
lock20_avail	A 1 Indicates Lock 20 is Unoccupied
lock21_avail	A 1 Indicates Lock 21 is Unoccupied
lock22_avail	A 1 Indicates Lock 22 is Unoccupied
lock24_avail	A 1 Indicates Lock 24 is Unoccupied
lock25_avail	A 1 Indicates Lock 25 is Unoccupied
lockages_20	Total Number of Lockages Completed at Lock 20
lockages_21	Total Number of Lockages Completed at Lock 21
lockages_22	Total Number of Lockages Completed at Lock 22
lockages_24	Total Number of Lockages Completed at Lock 24
lockages_25	Total Number of Lockages Completed at Lock 25
month	Indicates Simulation Month
local_total	Total Number of Local Vessel Tags Generated
pool_transit_time*	Mean Times for Pool Transit Distributions by Tow Type
position*	Indicates Lockage Type (Fly, Turnback, Exchange)

Table 18. Variables Defined in the Micros Saint 4.1 UMR Simulation Model

post_exit_time	Accumulated Time Remaining After a Tow Exits the System
pre_enter_time	Accumulated Simulation Time Prior to Tow Entrances
prior25*	Priority Indicator for Each Tow to be Selected from the Queue
prior24*	Priority Indicator for Each Tow to be Selected from the Queue
prior22*	Priority Indicator for Each Tow to be Selected from the Queue
prior21*	Priority Indicator for Each Tow to be Selected from the Queue
prior20*	Priority Indicator for Each Tow to be Selected from the Queue
queue_length*	Number of Vessels in each Lock Queue
roundtrips	Total Number of Tow Roundtrips Completed
roundtrips_large_tows	Total Number of Large Tow Roundtrips Completed
roundtrips_small_tows	Total Number of Small Tow Roundtrips Completed
run	Micro Saint 4.1 System Variable
sd_lock_time20*	Standard Deviations of Lockage Time Distributions - Lock 20
sd_lock_time21*	Standard Deviations of Lockage Time Distributions - Lock 21
sd_lock_time22*	Standard Deviations of Lockage Time Distributions - Lock 22
sd_lock_time24*	Standard Deviations of Lockage Time Distributions - Lock 24
sd_lock_time25*	Standard Deviations of Lockage Time Distributions - Lock 25
sd_pool_transit_time*	Standard Deviations of Pool Transit Time Distributions
seed	Micros Saint 4.1 System Variable to Seed Random Numbers
small_system_tow_time	Total Time Spent in the System by All Small Tows
small_tow_exit_prob*	Probability that a Small Tow does not Return to the System
small_tow_start_adj	Factor to alter Small Tow Inter-arrival Times
small_tow_start_rate*	Mean Time between Initial Lockages of Small Tows
small_tows	Limit on the Number of Small Tow Tags
small_tows_created	Running Count of Small Tow Tags Created
small_tows_released	Number of Small Tows That Entered the System
sum_queue	Total Number of Vessels in All Lock Queues
system_tow_time	Total Time Tows Are Operating in the System
tag	Micro Saint 4.1 System Variable
total_wait20	Total Accumulated Wait Time at Lock 20
total_wait21	Total Accumulated Wait Time at Lock 21
total_wait22	Total Accumulated Wait Time at Lock 22
total_wait24	Total Accumulated Wait Time at Lock 24
total_wait25	Total Accumulated Wait Time at Lock 25
tow_enter_large	Permit a New Large Tow to Enter the System
tow_enter_small	Permit a New Small Tow to Enter the System
tow_util20	Total Utilization Time for Tows at Lock 20
tow_util21	Total Utilization Time for Tows at Lock 21
tow_util22	Total Utilization Time for Tows at Lock 22
tow_util24	Total Utilization Time for Tows at Lock 24
tow_util25	Total Utilization Time for Tows at Lock 25

Table 18 (continued). Variables Defined in the Micros Saint 4.1 UMR Simulation Model

tow_wait20	Total Wait Time for Tows at Lock 20
tow_wait21	Total Wait Time for Tows at Lock 21
tow_wait22	Total Wait Time for Tows at Lock 22
tow_wait24	Total Wait Time for Tows at Lock 24
tow_wait25	Total Wait Time for Tows at Lock 25
tows_in_system	Total Number of Tows in the System
trip_start_time*	Time That Each Tow Last Arrived Upbound at Lock 25
vess_type*	0 = Local Vessel, 1 = Small Tow, 2 = Large Tow
wait_time*	Amount of Time That a Vessel Has Waited at a Lock
* indicates that the Micro Saint variable represents an array of variables	

Table 18 (continued). Variables Defined in the Micro Saint 4.1 UMR Simulation Model

End of Run Snapshot	Periodic Snapshot
clock	clock
large_tow_start_adj	lock_util[20]
large_tows_released	lock_util[21]
local20	lock_util[22]
local21	lock_util[24]
local22	lock_util[25]
local24	Queue_Length[20]
local25	Queue_Length[21]
lock_util[20]	Queue_Length[22]
lock_util[21]	Queue_Length[24]
lock_util[22]	Queue_Length[25]
lock_util[24]	roundtrips
lock_util[25]	roundtrips_large_tows
lockages_20	roundtrips_small_tows
lockages_21	run
lockages_22	Sum_Queue
lockages_24	tows_in_system
lockages_25	
post_exit_time	
pre_enter_time	
roundtrips	
roundtrips_large_tows	
roundtrips_small_tows	
run	
small_tow_start_adj	
small_tows_released	
total_wait20	
total_wait21	
total_wait22	
total_wait24	
total_wait25	
tow_util20	
tow_util21	
tow_util22	
tow_util24	
tow_util25	
tow_wait20	
tow_wait21	
tow_wait22	
tow_wait24	
tow_wait25	
tows_in_system	

Table 19. Variables Recorded in Snapshots in the Micros Saint 4.1 UMR Simulation Model

YEAR	*LOCK*	*Lockages*	*Total Vessel Wait Time (hours)*	*Total Vessel Lockage Time (hours)*	*Mean Wait Time (hours)*	*Mean Lockage Time (hours)*
2000	20	3,528	7,883	4,786	2.23	1.36
	21	3,704	6,686	5,086	1.81	1.37
	22	3,517	10,666	5,686	3.03	1.62
	24	3,800	8,304	5,391	2.19	1.42
	25	4,151	9,827	5,507	2.37	1.33
	Total	18,700	43,366	26,456	2.32	1.41
2001	20	3,164	6,113	4,107	1.93	1.30
	21	3,294	7,185	4,508	2.18	1.37
	22	3,162	13,882	4,966	4.39	1.57
	24	3,430	10,984	4,745	3.20	1.38
	25	3,841	15,810	4,829	4.12	1.26
	Total	16,891	53,975	23,156	3.20	1.37
2002	20	3,546	6,610	4,841	1.86	1.37
	21	3,708	5,266	5,077	1.42	1.37
	22	3,499	8,932	5,483	2.55	1.57
	24	3,742	14,479	5,438	3.87	1.45
	25	4,133	8,682	5,258	2.10	1.27
	Total	18,628	43,969	26,097	2.36	1.40
2003	20	3,126	4,393	4,203	1.41	1.34
	21	3,139	4,009	4,415	1.28	1.41
	22	3,000	5,977	4,803	1.99	1.60
	24	3,177	6,835	4,764	2.15	1.50
	25	3,519	5,950	4,728	1.69	1.34
	Total	15,961	27,163	22,914	1.70	1.44
Means All Years	20	3,341	6,250	4,484	1.86	1.34
	21	3,461	5,786	4,772	1.67	1.38
	22	3,295	9,864	5,234	2.99	1.59
	24	3,537	10,150	5,085	2.85	1.44
	25	3,911	10,067	5,081	2.57	1.30
	Total	17,545	42,118	24,656	2.39	1.41

Table 20. Vessel Lockages, Wait Times, and Lockage Times at UMR Locks Compiled from OMNI Data, 2000 through 2003

YEAR	*Vessel Type*	*Lockages*	*Total Vessel Wait Time (hours)*	*Total Vessel Lockage Time (hours)*	*Mean Wait Time (hours)*	*Mean Lockage Time (hours)*
2000	Large Tows	11,846	35,426	23,141	2.99	1.95
	Local Vessels	4,153	1,815	1,361	0.44	0.33
	Small Tows	2,701	6,125	1,954	2.27	0.72
	All Vessels	18,700	43,366	26,456	2.32	1.41
2001	Large Tows	10,443	45,348	20,126	4.34	1.93
	Local Vessels	3,742	1,577	1,169	0.42	0.31
	Small Tows	2,706	7,051	1,861	2.61	0.69
	All Vessels	16,891	53,975	23,156	3.20	1.37
2002	Large Tows	12,044	36,809	23,221	3.06	1.93
	Local Vessels	4,121	1,460	1,158	0.35	0.28
	Small Tows	2,463	5,699	1,717	2.31	0.70
	All Vessels	18,628	43,969	26,097	2.36	1.40
2003	Large Tows	10,179	21,895	20,337	2.15	2.00
	Local Vessels	3,632	1,270	1,074	0.35	0.30
	Small Tows	2,150	3,998	1,503	1.86	0.70
	All Vessels	15,961	27,163	22,914	1.70	1.44
Means All Years	Large Tows	11,128	34,869	21,706	3.14	1.95
	Local Vessels	3,912	1,531	1,190	0.39	0.30
	Small Tows	2,505	5,718	1,759	2.26	0.70
	All Tows	13,633	40,587	23,465	2.98	1.72
	All Vessels	17,545	42,118	24,656	2.39	1.41

Table 21. Vessel Lockages, Wait Times, and Lockage Times at UMR Locks by Vessel Type Compiled from OMNI Data, 2000 through 2003

Initial UMR Simulation Model

Selected Summary Statistics

	Tows	*Roundtrips Completed*	*Total Lockages Completed*	*Total Vessel Lockage Time (hours)*	*Total Vessel Wait Time (hours)*	*Wait Time per Lockage (hours)*
Mean	219.6	1,420.7	18,107.8	26,873.8	52,278.4	2.82
Std. Deviation	16.4	110.0	1,119.0	1,941.9	26,561.1	1.25

Lock Specific Summary Statistics

		Lock 20	*Lock 21*	*Lock 22*	*Lock 24*	*Lock 25*
Lockages	Mean	3,451.5	3,572.9	3,439.2	3,645.2	3,999.0
	Std. Deviation	248.7	223.7	227.5	225.0	224.8
Total Lock Time	Mean	5,031.7	5,219.0	5,746.3	5,455.6	5,421.2
	Std. Deviation	382.7	372.5	393.7	414.7	381.0
Total Wait Time	Mean	6,770.1	6,696.7	17,608.8	11,521.4	9,681.3
	Std. Deviation	1,964.9	1,858.0	15,059.1	5,751.2	3,145.0

Table 22. Selected Summary Statistics Compiled from 100 UMR Simulation Model Runs

Calibrated UMR Model

Selected Summary Statistics						
	Tows	*Roundtrips Completed*	*Total Lockages Completed*	*Total Vessel Lockage Time (hours)*	*Total Vessel Wait Time (hours)*	*Wait Time per Lockage (hours)*
Mean	209.2	1,364.3	17,438.5	25,855.8	41,199.3	2.36
Std. Deviation	17.0	117.9	1,291.0	2,350.0	23,095.1	1.1

Lock Specific Summary Statistics						
		Lock 20	*Lock 21*	*Lock 22*	*Lock 24*	*Lock 25*
Lockages	Mean	3,307.4	3,443.7	3,303.8	3,518.9	3,864.4
	Std. Deviation	276.6	242.1	234.5	243.5	243.4
Total Lock Time	Mean	4,794.0	4,923.2	5,455.5	5,263.1	5,239.9
	Std. Deviation	420.6	403.9	425.2	456.4	424.6
Total Wait Time	Mean	5,834.7	5,326.9	10,260.2	10,730.82	9,046.6
	Std. Deviation	1,928.9	1,471.4	4,701.5	6,998.6	3,457.4

Table 23. Selected Summary Statistics Compiled from 100 Calibrated UMR Simulation Model Runs

Results of 600 UMR Simulations Compared with 2000 - 2003 OMNI Data	Lock 20	Lock 21	Lock 22	Lock 24	Lock 25	Totals	Percent
Observed Lockages per Year	3,341	3,461	3,295	3,537	3,911	17,545	
Mean Simulated Lockages per Year	3,318	3,453	3,316	3,524	3,870	17,481	99.6%
Observed Wait Time per Year (hours)	6,250	5,786	9,864	10,150	10,067	42,117	
Mean Simulated Wait Time (hours)	5,926	5,421	10,775	10,734	9,301	42,157	100.1%
Observed Lock Usage per Year (hours)*	4,620	4,868	5,367	5,262	5,273	25,390	
Mean Simulated Lock Usage (hours)	4,823	4,951	5,485	5,292	5,268	25,820	101.7%
Observed Roundtrip Equivalents per Year**						1,363.3	
Mean Simulated Roundtrips per Year						1,366.8	100.3%
Standard Deviation of Simulated Roundtrips						119.1	
Mean Simulated Number of Tows per Year						209.0	
Mean Simulated Roundtrips per Year per Tow						6.5	
Mean Total Number of Tow-Hours Simulated						1,830,810.8	100.0%
Unrelated to the UMR System						1,111,247.8	60.7%
Used Creating UMR Roundtrips						719,563.0	39.3%
Mean Total Simulated Tow-Hours Used Locking						24,436.8	1.3%
Mean Total Simulated Tow-Hours Used Waiting						39,338.4	2.1%
Tow Hours per Simulated UMR Roundtrip						525.9	

* Includes Chamber Turnback Time

** Total Large and Small Tow Lockages / 10

Table 24. Selected Details of the Results of 600 UMR Simulations and Comparison with the 2000-2003 OMNI Data

Estimated Correlations of Simultaneous Number of Vessels in Simulated Lock Queues						
		Queue Length Lock 25	*Queue Length Lock 24*	*Queue Length Lock 22*	*Queue Length Lock 21*	*Queue Length Lock 20*
Queue Length Lock 25	Pearson Correlation	1.000	0.462	0.362	0.204	0.146
	Sig. (2-tailed)		0.000	0.000	0.000	0.000
	N	1,200	1,200	1,200	1,200	1,200
Queue Length Lock 24	Pearson Correlation	0.462	1.000	0.530	0.242	0.248
	Sig. (2-tailed)	0.000		0.000	0.000	0.000
	N	1,200	1,200	1,200	1,200	1,200
Queue Length Lock 22	Pearson Correlation	0.362	0.530	1.000	0.379	0.330
	Sig. (2-tailed)	0.000	0.000		0.000	0.000
	N	1,200	1,200	1,200	1,200	1,200
Queue Length Lock 21	Pearson Correlation	0.204	0.242	0.379	1.000	0.384
	Sig. (2-tailed)	0.000	0.000	0.000		0.000
	N	1,200	1,200	1,200	1,200	1,200
Queue Length Lock 20	Pearson Correlation	0.146	0.248	0.330	0.384	1.000
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	
	N	1,200	1,200	1,200	1,200	1,200

Table 25. Bivariate Pearson Correlation Coefficients for Simultaneous Lock Queue Sizes from 100 UMR Simulation Model Runs

	Lock 20	*Lock 21*	*Lock 22*	*Lock 24*	*Lock 25*	*Totals*	*Change From Existing Policy*
Mean Simulated Lockages per Year	3,329	3,463	3,331	3,532	3,882	17,538	+57
Mean Simulated Wait Time (hours)	5,930	5,130	9,490	10,450	7,570	38,569	-3,588
Mean Simulated Lock Usage (hours)	4,806	4,906	5,434	5,282	5,258	25,688	-132
Mean Simulated Roundtrips per Year						1,372.1	+5.3
Standard Deviation of Simulated Roundtrips						119.9	+0.8
Mean Simulated Number of Tows per Year						210.4	+1.4
Mean Simulated Roundtrips per Year per Tow						6.5	0.0
Mean Total Number of Tow-Hours Simulated						1,843,323.0	+12,421.2
Unrelated to the UMR System						1,124,509.8	+13,262.0
Used Creating UMR Roundtrips						718,813.2	-749.8
Mean Simulated Tow-Hours Used Locking						24,303.5	-133.3
Mean Simulated Tow-Hours Used Waiting						35,783.3	-3,555.1
Tow Hours per Simulated UMR Roundtrip						523.3	-2.6

Table 26. Selected Summary Results of 600 UMR Simulation Model Runs Employing a SPF Queue Dispatch Policy

		Sum of Squares	df	Mean Square	F	Sig.
Simulated Tows	Between Groups	612.0	1	612.0	2.138	.144
	Within Groups	342,994.6	1198	286.3		
	Total	343,606.7	1199			
Simulated Lockages	Between Groups	956,601.8	1	956,601.8	.660	.417
	Within Groups	1,736,898,448.9	1198	1,449,831.8		
	Total	1,737,855,050.7	1199			
Simulated Lock Utilization	Between Groups	5,207,268.6	1	5,207,268.6	1.154	.283
	Within Groups	5,404,433,477.4	1198	4,511,213.3		
	Total	5,409,640,746.0	1199			
Simulated Wait Time	Between Groups	3,862,224,282.0	1	3,862,224,282.0	13.148	.000
	Within Groups	351,914,879,209.3	1198	293,751,986.0		
	Total	355,777,103,491.4	1199			
Total System Tow Time	Between Groups	168,641,168.1	1	168,641,168.1	.031	.861
	Within Groups	6,575,251,330,473.2	1198	5,488,523,648.1		
	Total	6,575,419,971,641.2	1199			
Tow Time per Roundtrip	Between Groups	1,995.9	1	1,995.9	9.277	.002
	Within Groups	257,744.2	1198	215.1		
	Total	259,740.1	1199			
System Time per Tow	Between Groups	212,839.7	1	212,839.7	6.463	.011
	Within Groups	39,452,889.0	1198	32,932.3		
	Total	39,665,728.7	1199			
Total Roundtrips	Between Groups	8,020.2	1	8,020.2	.560	.455
	Within Groups	17,167,916.2	1198	14,330.5		
	Total	17,175,936.4	1199			

Table 27. Analysis of Variance for Differences in Means of Selected Simulation Variables

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The NETS research program is developing a series of practical tools and techniques that can be used by Corps navigation planners across the country to develop consistent, accurate, useful and comparable information regarding the likely impact of proposed changes to navigation infrastructure or systems.

The centerpiece of these efforts will be a suite of simulation models. This suite will include:

- A model for forecasting international and domestic traffic flows and how they may be affected by project improvements.
- A regional traffic routing model that will identify the annual quantities of commodities coming from various origin points and the routes used to satisfy forecasted demand at each destination.
- A microscopic event model that will generate routes for individual shipments from commodity origin to destination in order to evaluate non-structural and reliability measures.

As these models and other tools are finalized they will be available on the NETS web site:

http://www.corpsnets.us/toolbox.cfm

The NETS bookshelf contains the NETS body of knowledge in the form of final reports, models, and policy guidance. Documents are posted as they become available and can be accessed here:

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